

CORPS OF ENGINEERS, U. S. ARMY

MISSISSIPPI RIVER COMMISSION

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BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR,  
LAKE SUPERIOR, MINNESOTA

MODEL INVESTIGATION



TECHNICAL MEMORANDUM 2-296

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

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FRONTISPICE. Proposed ultimate plant and harbor development, East Beaver Bay, Minnesota

## PREFACE

The Oglebay Norton and Company, Cleveland, Ohio, requested the Waterways Experiment Station to conduct a hydraulic model investigation of the proposed East Beaver Bay Harbor in a letter dated 30 June 1947. Authority to perform the investigation was granted by the Chief of Engineers, U. S. Army, 28 July 1947.

The investigation involved (1) study of problems relating to the over-all harbor design, and (2) study of the stability of the proposed rubble breakwaters. This report is concerned with the breakwater stability study only; the harbor-design study is reported in Technical Memorandum No. 2-295, July 1949.

The tests reported herein were conducted during the period from January to June 1948. Experiment Station engineers actively connected with the investigation were Messrs. E. P. Fortson, Jr., F. R. Brown, R. Y. Hudson, R. A. Jackson, and J. H. McInnis.

At various times during the course of the investigation Messrs. H. J. Taylor, F. J. Smith, C. A. Arnold, H. K. Martin, L. Balderson, and D. S. Young of the Oglebay Norton and Company; Mr. I. H. Wynne of the Reserve Mining Company; Mr. E. T. Davis of the Wheeling Steel Corporation; Mr. C. L. Kingsbury of the American Rolling Mill Company; and Captain H. F. Wiersch of the Columbia Transportation Company visited the Experiment Station to attend conferences and witness model demonstrations.

The prototype wind-wave analysis conducted in conjunction with this study was made by Clark and Flohr, Engineering Services, of Vicksburg, Miss., under the supervision of Waterways Experiment Station engineers.

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## SUMMARY

A hydraulic model study was performed on a 1:30-scale model to determine the relative stability and maintenance costs of two types of rubble breakwaters proposed for use at East Beaver Bay Harbor, Minnesota. A comprehensive wind-wave analysis also was conducted to determine the dimensions, directions of approach, and frequency of occurrence of waves which will attack the breakwaters. The results of the model tests and the prototype wind-wave analysis were used jointly to estimate the quantities of breakwater material required for maintenance during breakwater construction and for a 40-year period after construction.

It was concluded from the results of the model tests and the wind-wave analysis that:

- a. The stability of rubble breakwaters is improved by the process of damage and repair.
- b. When constructed by dumping material from the sides and lakeward end, rubble breakwaters of the design tested in this investigation would be unstable under the attack of waves greater than about 10 ft in height.
- c. When constructed by the conventional method of dumping materials from floating equipment, rubble breakwaters of the design tested in this investigation would provide adequate protection to the proposed harbor without requiring extensive repairs.
- d. Rubble breakwaters constructed by the end- and side-dump method would require about three times as much material for maintenance during construction, and about two and one-half times as much material for maintenance for a 40-year period after construction, as breakwaters constructed by dumping material from floating equipment.
- e. Although model test results show that the rubble breakwater of conventional design would require less material for construction and maintenance than would one designed for construction by the end- and side-dump method, it does not follow that the conventional-type breakwater

would prove to be the most economical. To determine the more economical breakwater of the two types of designs tested, it will be necessary to take into consideration the unit costs of construction, using the two methods of placing the material, and the difference in the costs of financing over a period of years.

BREAKWATER STABILITY

EAST BEAVER BAY HARBOR, LAKE SUPERIOR, MINNESOTA

Model Investigation

PART I: INTRODUCTION

1. The full-scale breakwaters with which this model study was concerned were rubble-mound structures tentatively selected for use in protecting a proposed harbor on the north shore of Lake Superior from storm-wave action. The Oglebay Norton and Company in planning the construction of an ore-processing plant about 2 miles northeast of the village of East Beaver Bay, Minnesota, (see vicinity map on plate 1) considered that an artificial harbor adjacent to the plant would be necessary to provide protection for ships servicing the plant during construction and operation and transporting processed ore to mills located along the shores of the Great Lakes.

2. The site of the proposed harbor is exposed to wind waves generated by storms from directions clockwise between northeast by east and southwest. Storms from the directions northeast by east to east and southwest to south-southwest are the most critical. A breakwater system to provide optimum protection from storm-wave action was developed from the results of a companion model study<sup>1</sup> conducted by the Waterways Experiment Station (see plate 1).

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<sup>1</sup> Waterways Experiment Station Technical Memorandum No. 2-295, "Wave Action and Breakwater Location, East Beaver Bay Harbor, Lake Superior, Minnesota; Model Investigation," July 1949.

3. Because of the size of waves which occur and the great depth of water which exists at East Beaver Bay, large quantities of rock will be required to construct the needed breakwaters. This fact together with the high unit cost of placing the material by the conventional method of dumping from scows or barges posed a very difficult problem in arriving at an economical breakwater design. After consideration of this problem, the rubble breakwater shown in the inset on plate 1 was designed to take advantage of a combination of natural conditions existing at the proposed harbor site: an adequate rock supply is available near the shore ends of the proposed breakwaters; and excavation and removal of large quantities of this rock will be necessary preparatory to construction of the proposed processing plant. To reduce the cost of construction still further, it was proposed that rock be dumped from trucks over the lake-ward end and sides of the breakwaters, using the top portion of the class-A material section as a roadway. The original breakwater was devised especially for this type of construction in order to eliminate as much as possible the more costly procedure of dumping from floating equipment.

4. It was recognized that breakwaters constructed by the conventional method of dumping rubble from floating equipment are more stable (all conditions being equal) than the end-dumped type, because protective cap rock can be placed as soon as the underwater section is brought to grade; also the protective cap rock can be extended to any desired depth. Although the end-dump method might result in a less stable structure, it was thought that this type breakwater could be constructed and maintained more economically than a breakwater constructed by conventional

methods. However, to determine the most economical type of breakwater design, it was necessary to obtain information concerning the quantities of material required for initial construction and maintenance both during and after construction for both types.

5. Model tests were performed to determine the relative stabilities of the two types of breakwaters obtained from consideration of the methods of construction mentioned above and the quantities of material eroded from the breakwater sections by waves of various dimensions. A wind-wave analysis was conducted to obtain data concerning the dimensions, directions of approach, and frequency of storm waves which occur at the prototype site. The data and information provided by the model tests and the prototype wind-wave analysis, in conjunction with unit costs for placing the different classes of material, furnish a basis for selection of the most durable and economical breakwater designs.

## PART II: THE MODEL

Design

6. A 1:30 scale was selected for use in the breakwater stability study as being the largest possible scale consistent with the capabilities of the available wave-generating device and the maximum depth of water in the wave tank. After the linear scale was selected, the model was designed in accordance with Froude's<sup>2</sup> model laws. Based on Froude's laws, a linear scale of 1:30, and a specific weight scale of 1:1, the following scale relationships were derived:

<u>Characteristic</u>	<u>Dimension<sup>3</sup></u>	<u>Model-Prototype Scale</u>
Length	L	$L_r = 1:30$
Area	$L^2$	$A_r = L_r^2 = 1:900$
Volume	$L^3$	$V_r = L_r^3 = 1:27,000$
Time	T	$T_r = L_r^{1/2} = 1:5.48$
Velocity	$L/T$	$V_r = L_r^{1/2} = 1:5.48$
Unit Pressure	$F/L^2$	$P_r = L_r^2 = 1:30$
Specific Weight	$F/L^3$	$\gamma_r = 1:1$
Force	F	$F_r = L_r^3 \gamma_r = 1:27,000$
Weight	F	$W_r = L_r^3 \gamma_r = 1:27,000$
Energy	FL	$E_r = L_r^4 \gamma_r = 1:810,000$

<sup>2</sup> ASCE Manual of Engineering Practice, Number 25, "Hydraulic Models," p. 9 and 43.

<sup>3</sup> In terms of force, length, and time.

Description

7. The study was conducted in a concrete wave tank 5 ft high x 18 ft wide x 119 ft long, one side of which was equipped with a glass viewing window. At the end of the tank receiving the wave attack porous concrete blocks were installed on a slope of 1 on 5 to control reflection of the waves (see photograph 1). The model breakwaters were placed across the tank normal to its longitudinal axis and approximately 90 ft from the wave generator; the bottom area at the test section was molded in sand. Sounding equipment, consisting of a graduated board for measuring horizontal distances parallel with the longitudinal axis of the breakwater and a graduated rod for measuring vertical distances, was used for cross sectioning and was operated from the top of the wave tank directly above the breakwaters. Model waves were generated by a plunger-type wave machine and wave heights were measured and recorded by electrical apparatus designed and constructed especially for this purpose.<sup>4</sup>

8. The model breakwaters and the rock with which they were constructed are described in Part III of this report.

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<sup>4</sup> For a detailed description of the wave-height measuring and recording apparatus, see Waterways Experiment Station Technical Memorandum No. 2-237, "Model Study of Wave and Surge Action, Terminal Island, San Pedro, California," dated September 1947.

### PART III: THE TESTING PROGRAM

#### The Testing Procedure

9. The model breakwaters were constructed in a dry tank, after which the tank was flooded to the proper depth and the breakwaters subjected to the attack of test waves until all apparent erosion and displacement of breakwater materials ceased. The breakwaters were considered stabilized by the forces of wave action when an additional period of wave attack caused no further displacement. The extent of the progressive displacement of breakwater materials was determined by frequent cross-sectioning. Soundings were taken at 0.5-ft stations along a 10-ft length of breakwater in the middle of the wave tank. The extremities, adjacent to the walls, were not sounded because of the unnatural effects of the wave-tank walls on this portion of the breakwaters. After the model breakwaters had been stabilized by wave action, they were repaired by replacing the rock which had been displaced from the design section and again subjected to wave attack. In this way the increase in stability gained by a breakwater through the process of damage and repair was determined.

#### Description of Breakwaters Tested

##### Types of breakwater sections

10. Stability tests were conducted on two types of breakwater designs, the elements of which are shown on plate 2. Design 1 was the original design breakwater, previously discussed and shown as an inset on plate 1, except for changes in the specifications of the class-C cap rock

and the class-B material. Design 1A was the same as design 1, except that the crown elevation was raised from +8.4 ft lwd<sup>5</sup> to +14.4 ft lwd. It was proposed to construct this type breakwater by dumping the class-A and class-B materials over the end and sides of the breakwater, and by placing class-C cap rock by crane from floating equipment. Design 2, and its alternate design 2A, were selected by the Waterways Experiment Station as typical designs which involve construction by floating equipment. Design 2 was very similar to design 1, except that the thickness of the cap rock was increased from 6 ft to 18.4 ft and a 6-1/4-ft thickness of class-B material was placed between the class-C material cap rock and the class-A material core. Design 2A was the same as design 2 except that the crown elevation was raised from +8.4 ft lwd to +14.4 ft lwd. To determine the amount of damage caused by wave action during breakwater construction, the A- and B-material sections of designs 1 and 2 were tested without the protection of the class-C cap rock.

#### Description of breakwater materials

11. Similarity between model and prototype breakwater materials is a significant requirement in attaining dynamic similarity between model and prototype. To satisfy the requirements of similitude, especially with respect to specific weight, the Waterways Experiment Station requested Oglebay Norton and Company to furnish materials for model use similar to those which will be used for constructing the prototype breakwaters. Because the necessary quarrying equipment was not available at

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<sup>5</sup> Low water datum for Lake Superior is 601.6 ft above mean tide at New York City.

the proposed East Beaver Bay Quarry site, rock for model use was obtained from the Zenith Quarry at Duluth, Minnesota. The Zenith Quarry rock (basalt) had a specific weight of about 175 lb per cu ft.

12. Specifications for the model breakwater materials were based on an estimate of breakage at the East Beaver Bay Quarry. Estimates of quarry breakage were as follows:

<u>Per Cent of Total</u>	<u>Weight of Rock</u>
10	Over 10 tons
30	1 to 10 tons
60	Less than 1 ton

Of the material weighing less than one ton, it was estimated that five per cent would weigh less than 5 lb with the remaining 95 per cent having an even gradient between 5 lb and one ton.

13. The model breakwater materials were sized and proportioned according to the following specifications:

<u>Per Cent of Total</u>	<u>Prototype Weight</u>
<u>Class-C Cap Rock</u>	
75	10-12 tons
25	12-14 tons
<u>Class-B Material</u>	
35	1-2 tons
30	2-4 tons
20	4-6 tons
10	6-8 tons
5	8-10 tons
<u>Class-A Material</u>	
5	1-5 lb
15	5-100 lb
30	100-500 lb
30	500-1000 lb
20	1000-2000 lb

#### Selection of Test Conditions

14. All stability tests were conducted using a water depth of 63 ft with the still-water level at +1.5 ft lwd. A water depth of 63 ft was selected as the maximum possible within the limitations imposed by the existing wave tank and wave machine. This depth was adequate to prevent deformation of the attacking waves by material eroded from the upper part of the breakwater and deposited at the toe of the breakwater slope. A still-water level of +1.5 ft lwd was selected based on the average monthly mean level of Lake Superior, which is +0.5 ft lwd, and allowing 1 ft for the effects of wind and seiche action on local water levels during storms. The height and length of the test waves selected were 6 ft x 160 ft, 10 ft x 180 ft, and 14 ft x 240 ft. The 6-ft x 160-ft test wave was selected as the smallest wave likely to damage the breakwaters, and the 14-ft x 240-ft wave was considered the largest wave likely to occur within the economic life span of the proposed structures. The 10-ft x 180-ft test wave was intermediate between the two extremes. All tests were conducted using waves advancing normal to the longitudinal axis of the breakwater. The test waves used were selected before completion of a wind-wave analysis of this area which is discussed in Part IV of this report.

#### Presentation and Interpretation of Test Results

15. Photograph 1 is a general view of the wave tank and photographs 2-25 are end views of the various breakwater test sections before and after wave attack, taken through the observation window in the side

of the tank. The breakwater cross sections on plates 3-14 show the form of the test sections before wave attack and after they had been stabilized by wave action. The curves on plates 15-20 indicate the quantities of material, in cubic yards per linear foot of breakwater, eroded from the test sections plotted as a function of duration of wave attack. In interpreting the results of the model tests it should be borne in mind that damage to the model breakwaters represents the damage done by a train of waves of practically uniform size, attacking normally a rubble mound constructed by hand, until equilibrium between the resisting and opposing forces was attained. Although it is impossible to reproduce exactly the interlocking characteristics of the individual rocks which are obtained in a prototype structure, the model results are considered to be sufficiently accurate for solution of the problems involved.

## PART IV: WIND-WAVE ANALYSIS

Purpose and Method of Performing Analysis

16. The Waterways Experiment Station requested a wind-wave analysis to obtain reliable information concerning the dimensions and frequency of occurrence of waves which will attack the prototype breakwaters. The basic data upon which the wind-wave analysis was founded were obtained from the U. S. Weather Bureau at Duluth, Minnesota, and consisted of records of the direction, velocity, and duration of winds for the period 1915 to 1947. Only winds with a velocity greater than 10 mph and from the northeast, east, southeast, south, and southwest directions were used in the analysis. The dimensions, directions of approach, and number of occurrences of various-size prototype storm waves were determined from the wind records by application of the principles of wave forecasting as developed by Sverdrup and Munk<sup>6</sup> and Stevenson's formula<sup>7</sup> (plate 21). The analysis was prepared by Clark and Flohr, Engineering Services, Vicksburg, Mississippi, under the supervision of the Waterways Experiment Station.

Results of Analysis

17. The results of the wind-wave analysis are presented in tables 1 to 4 and on plates 21-24. The geographical location of the proposed

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<sup>6</sup> H. U. Sverdrup and W. H. Munk, "Wind, Sea, and Swell; Theory of Relations for Forecasting," (U. S. Navy Hydrographic Office Publication No. 601; Washington: March 1947).

<sup>7</sup> Thomas Stevenson, "The Design and Construction of Harbours, A Treatise on Maritime Engineering," (3rd ed.; Edinburgh: 1886), pp. 26-40.

East Beaver Bay Harbor is such that storm winds from the northeast to southwest directions, in a clockwise sense, generate waves which are critical with respect to the design of the harbor and harbor structures. The data in tables 1 and 2 show that storms from the northeast to east directions are more severe and occur more frequently than storms from other directions. The height of the maximum waves from the northeast to east directions is about 16 ft. Waves of this height have a frequency of one occurrence in about 30 years. At least one storm from the directions northeast to east, with heights ranging from 11 to 15 ft, can be expected to occur each year. Storm waves of lesser height from these directions occur several times yearly. The height of the maximum waves from the southeast to southwest directions is about 13 ft. Waves of this height have a frequency of one occurrence in about 30 years. Waves from the southeast to southwest directions with heights ranging from 9 ft to 12 ft can be expected to occur one time in about seven years. The data in tables 3 and 4 show that most of the severe storms from the northeast to southwest directions occur during the months from March to July. The characteristics of typical prototype storms from the northeast and southwest directions are shown on plates 22 to 24. The data shown on these plates consist of wave heights and wind velocity plotted, separately, against duration for typical storms which result in 6-ft, 10-ft, and 14-ft waves (maximum) from the northeast direction, and typical storms which result in 6-ft and 10-ft waves from the southwest direction. In general, these data show that the durations of the maximum wave heights and wind velocities from the northeast direction are greater than those from the southwest direction. The large dimensions of storm waves from the

northeast and east directions are the result of long fetches and high wind velocities.

## PART V: ESTIMATE OF STORM DAMAGE TO BREAKWATERS

Method of Estimating Storm DamageBreakwater construction schemes

18. The results of the companion model study of wave action and breakwater location at East Beaver Bay Harbor showed that the breakwater system designated as plan 4 would provide adequate protection to the proposed harbor. Plan 4 (plate 1) consists of rubble-mound breakwaters from shore to Pancake Island (north breakwater arm) and from shore to Gull Island (south breakwater arm) and a cellular structure between Pancake Island and the navigation opening off Gull Island. Observational tests on the wave-action model to investigate overtopping showed that the rubble-mound breakwaters between Pancake Island and shore should be constructed to a crown elevation of at least +14 ft lwd, and that unless absolute protection from overtopping was required, a crown elevation of from +8 ft to +10 ft lwd would be adequate for the breakwater arm between Gull Island and shore. Therefore, for the purpose of estimating the quantities of breakwater material required for initial construction, maintenance during construction, and maintenance for a 40-year period after construction, schemes were devised using various combinations of crown elevations for the north and south breakwater arms of plan 4. The designation and description of these schemes are as follow: construction scheme A consists of the north and south breakwater arms of plan 4 constructed to a crown elevation of +8.4 ft lwd; construction scheme B consists of the north and south breakwater arms of plan 4 constructed to a crown elevation of +14.4 ft lwd; and construction scheme C consists of

the north breakwater arm constructed to a crown elevation of +14.4 ft lwd, with the south breakwater arm constructed to a crown elevation of +8.4 ft lwd. In view of the fact that the cellular breakwater between Pancake Island and the navigation opening will be constructed of tailings (ore-processing plant waste), surmounted by circular concrete cells filled with tailings, no stability tests were made on this section of the breakwater system.

Assumed schedules for breakwater construction

19. Before the amount of damage to the breakwaters (during and after construction) could be estimated, certain assumptions were necessary concerning the months of the year during which construction would be in progress and the rate of progress of constructing the different material sections. The following assumptions were made concerning the construction of designs 1 and 1A: (a) work would begin 1 March and end 31 October; (b) construction of the A- and B-material sections would require six months; (c) construction of the C-material section would require two months; (d) equal lengths of breakwater sections would be completed each month; and (e) A- and B-material sections would be complete before work on the C-material section was begun. For construction of designs 2 and 2A, it was assumed that: (a) breakwater construction would begin 1 March; (b) A- and B-material sections would be completed by 31 October; (c) construction of the C-material section would be completed by 30 November, lagging construction of the A- and B-material sections by one month; and (d) equal lengths of breakwater sections would be completed each month. Although the actual dates upon which work will begin, the

phasing of the work, and rate of progress will depend primarily upon the contractor, it is believed that the assumptions are sufficiently accurate for the purposes of this study.

Discussion of estimating procedure

20. Estimates of breakwater damage by prototype storms were made by correlating the model test results with the results of the wind-wave analysis described in the preceding part. Data necessary for making such an estimate involved determining the amount of damage caused by each size wave from each of the critical directions on each breakwater tested as a function of duration of wave attack. It was assumed that the amount of damage caused by wave action on a rubble mound varied directly with wave energy. Therefore, to obtain basic model data concerning the amount of damage caused by wave action as a function of duration of wave attack and wave energy, 6-ft, 10-ft, and 14-ft test waves were used (separately) for testing. The curves on plates 15 to 20 show the resulting model data for the various breakwater designs in terms of cubic yards of material displaced per foot length of breakwater. The amount of damage which will be caused by waves of various dimensions in the prototype (see tables 1 and 2) was determined by interpolation from the basic data shown on plates 15 to 20. Information as to the duration of wave attack on prototype breakwaters, by each size prototype wave from the critical directions, is not directly available from the results of the wind-wave analysis. However, data are available concerning the duration of typical prototype storms. These data are shown on plates 22 to 24 as wave heights plotted against duration for typical storms which generate waves increscent to

6 ft, 10 ft and 14 ft in height from the northeast direction, and to 6 ft and 10 ft in height from the southwest direction. The duration of attack of each size wave (height intervals of 1 ft) less than and equal to the height of each group of typical prototype storm waves was determined from the data shown on plates 22 to 24. The amount of damage caused by each size wave of each group of typical prototype storms, as a function of duration of wave attack, was determined from the interpolated damage curves. The combination of wave height and duration of attack which caused the maximum amount of damage was assumed to represent the amount of damage which would be caused by each of the typical prototype storms. The amount of damage caused by waves of sizes other than 6 ft, 10 ft, and 14 ft was interpolated from the damage curves described above. The height-duration combination for waves from the northeast to east directions was determined from the characteristics of typical northeast storms, and the characteristics of typical storms from the southwest direction were used to determine the height-duration combination of waves from the southeast to southwest directions. Table 5 shows the estimated storm damage to the breakwaters caused by waves from 2 ft to 16 ft in height from the northeast to east directions, and table 6 shows the estimated storm damage caused by waves from 2 ft to 13 ft in height from the southeast to southwest directions.

#### Estimate of Storm Damage to Breakwater Sections

##### Damage during breakwater construction

21. Storms which may be expected to occur from the northeast to east directions and from the southeast to southwest directions during a

typical year are shown in tables 3 and 4, respectively. Storms from the northeast to east directions were used to estimate the amount of damage to the north breakwater arm (plate 1); storms from the southeast to southwest directions, to estimate the amount of damage to the south breakwater arm. To estimate the amount of damage to the length of breakwater completed by the end of each month during breakwater construction, the order of occurrence of the storms was arranged in ascending order of intensity from the least storm wave to the largest storm wave, and then in descending order from the largest storm wave to the least storm wave. This arrangement of occurrence of storms allows a more conservative estimate of the amount of damage than if the occurrence of the storms were arranged so that the largest storm occurred at the beginning or end of each month. The amount of damage to the A- and B-material sections of designs 1 and 1A was estimated by assuming that all storm damage to these sections would be repaired immediately. The amount of damage to the C-material sections of designs 1 and 1A was estimated by assuming that storm damage to the C-material section would not be repaired until after construction of the breakwater was completed. The total amount of damage to the length of A- and B-material sections of designs 1 and 1A completed each month was estimated by applying the amount of damage per unit length of breakwater (obtained from tables 5 and 6) to one half the length of breakwater completed during the current month. This procedure was also used for estimating the damage to the C-material sections of designs 1 and 1A. The amount of damage to the length of breakwater completed in the previous months was estimated by applying the damage caused by the storms of the current month, to the total length of breakwater completed

prior to the current month.

22. The amount of damage to the A- and B-material sections of breakwater designs 2 and 2A was estimated by applying the damage per unit length of breakwater caused by the worst storm of the month to one half the length of A- and B-material sections completed during the current month. The worst storm of the month was used because it was assumed that the A- and B-material sections would not be repaired during construction. Because construction of the C-material section was assumed to lag construction of the A- and B-material sections by one month's work, the damage per unit length of breakwater caused by the worst storm of the current month was applied to one half the length of A- and B-material sections completed prior to the current month. The procedure used for estimating the amount of damage to the C-material section of breakwater designs 2 and 2A consists of applying the damage per unit length of breakwater caused by the worst storm of the month to one half the length of the C-material section completed each month and to all of the C-material section previously completed.

23. The following procedure was used for calculating the damage to a section of breakwater which had been damaged and repaired previously:

- (a) if the height of the wave causing damage was equal to or less than the height of the previous wave, the amount of damage to a repaired section (as shown by model tests) was used for the second repair, one half of the damage to a repaired section was used for the third repair, and so on until the amount of damage was less than 2 cu yd per foot length of breakwater; (b) if the height of the wave causing damage was larger than the height of the previous wave, the amount of damage to an original

section was used for the second repair; for the third repair, the amount of damage to a repaired section was used; then one half of the repaired damage and so on until the damage was less than 2 cu yd per foot length of breakwater.

#### Damage to completed breakwater

24. It was assumed that the 33-year period of wind-wave analysis was indicative of a typical storm cycle, and that the cycle would repeat itself every 33 years. The capital investment for the East Beaver Bay project will be retired at the end of 40 years; therefore, the quantity of breakwater material required for maintenance was estimated for a 40-year period instead of the 33-year period of record. The year 1932 of the analyzed weather records was selected as the typical year during which both breakwater arms would be completed. It was also assumed that repairs to the breakwater would be made yearly during the months of July and August when few storms occur. In estimating the amount of damage to the breakwaters for the 40-year period, the worst storm which occurred during each year was used to calculate the yearly damage. The procedure for estimating the damage to a completed breakwater section which had been repaired previously was the same as described in paragraph 23. Table 7 shows the estimated quantities of material required for initial construction, maintenance during construction, and maintenance for a 40-year period after construction using designs 1, 1A, 2 and 2A and construction schemes A, B and C. Breakwater designs 1 and 1A require about three times more material for maintenance during construction, and about two and one-half times more material for maintenance for a 40-year period

after construction, than that required by breakwater designs 2 and 2A. However, the total quantity of material required for initial construction, maintenance during construction, and maintenance for a 40-year period after construction would average only about 12 per cent more for breakwater designs 1 and 1A than for designs 2 and 2A.

## PART VI: CONCLUSIONS

25. Based upon the results of the model tests and the estimated quantities of breakwater material required for initial construction, maintenance during construction, and maintenance for a 40-year period after construction, it was concluded that:

- a. Breakwater designs 1 and 1A would be unstable during breakwater construction under the attack of waves above about 10 ft in height.
- b. The stability of the design-1 breakwater would be improved by raising the crown elevation from +8.4 ft lwd to +14.4 ft lwd (design 1A). However, for both designs 1 and 1A, the structure should be damaged by wave action and then repaired one or more times in order to obtain a breakwater which will be stable under the attack of waves above 10 ft in height.
- c. The small size of the protective cap-rock section, and the absence of a blanket of B material for protecting the top of the class-A material section during breakwater construction, are the elements of breakwater designs 1 and 1A which cause these structures to be unstable under the attack of the larger waves which occur at Beaver Bay.
- d. Based on the total estimated quantities of breakwater material required for initial construction, maintenance during construction and maintenance for a 40-year period after construction designs 2 and 2A are more efficient than designs 1 and 1A. However, because of the differences in the unit costs of handling materials for initial construction and over-all maintenance for the two different types of breakwaters it is necessary to apply unit costs of construction, and interest rates to the funds expended, in order to select the most economical breakwater design.

## **TABLES**

Table 1  
**WIND-WAVE ANALYSIS**  
**STORMS OCCURRING FROM EAST AND NORTHEAST DIRECTIONS**

Wave Heights, feet	2-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
Wave Periods, seconds	3.6-4.5	4.5-4.8	4.8-5.1	5.1-5.3	5.3-5.5	5.5-5.7	5.7-6.0	6.0-6.2	6.2-6.3	6.3-6.6	6.6-7.0	7.0-7.2
<u>Year</u>												
1915	29	5	5	3	1	5		1		1		
1916	28	6	6	5	1	3		3		1	1	1
1917	24	2	6	3	3	2	3			1		
1918	36	3	5	1	1	3	3	2	2			
1919	32	3	1	5	2	3	2			1		1
1920	32	6	2	1	1	2	3		2		1	
1921	37	7	4	2	3			1				
1922	28	9	6	1	1	3		3		1		
1923	26	5	3	2			1	2				
1924	13	3	5	1	2	1		1		2		1
1925	24	7	1	3	1	1			2			
1926	29	4	2	4	1	2	1	3				
1927	32	2	3	3	2	4				1		
1928	30	4	2		1	2						
1929	17	6	4	2								
1930	28	2	1	2				1				
1931	22	5	2	1			1					
1932	27	4	3	2		2		2				
1933	33	5		4	2			2				
1934	33	5	1	2	2							
1935	23		4	4	1		1					
1936	25	8	3	3					1			
1937	26	7	3	2	1		1		1			
1938	28	7	1	4	2		1					
1939	36	5	3	1	1	2			1		1	
1940	36	3	1	2	2		2					
1941	25	4	1	3								
1942	34	7	3	4		1						
1943	21	6	2	3		2		1			1	
1944	24	4	2	3		1					1	
1945	30	4	1	1	1			1				
1946	26	9	4	1				1				
1947	20	6	1	1	1	2		1				

Notes: Tabulated from data prepared by Clark and Flohr  
 Wave periods shown are the average periods of east and northeast storm waves

Table 2

WIND-WAVE ANALYSIS  
STORMS OCCURRING FROM SOUTHEAST, SOUTH AND SOUTHWEST DIRECTIONS

Wave Ht, ft	2-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
Wave Per., sec	2.8-3.8	3.8-4.1	4.1-4.4	4.4-4.6	4.6-5.0	5.0-5.4	5.4-5.9	5.9-6.4	6.4-6.9
Year	Number of Occurrences								
1915	23	2		2		1			
1916	46	5	1	1	1				1
1917	24	4	2				1		
1918	40	5	5		3			1	
1919	36	6	1	1					
1920	26	4	2						
1921	36	7	1	1					
1922	36	5	4	1					
1923	40	3	3						
1924	36	4	3						
1925	43	6	2	2	1				
1926	32	3	1	1			1		
1927	26	2	1						
1928	28	1		1					
1929	25	2							
1930	24	2			1				
1931	27		2						
1932	31	2							
1933	33	2							
1934	24	1	1						
1935	26								
1936	23	2	1	1					
1937	19								
1938	27	2							
1939	29		1						
1940	23	1							
1941	29	1							
1942	33	1							
1943	28			1					
1944	25								
1945	29								
1946	16				1				
1947	20	2				1			

Notes: Tabulated from data prepared by Clark and Flohr  
Wave periods shown are the average periods of southeast, south and southwest waves

Table 3

WIND-WAVE ANALYSIS  
STORMS OCCURRING DURING A TYPICAL YEAR; WAVES FROM EAST AND NORTHEAST DIRECTIONS

Wave Ht, ft	2-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
Wave Per, sec	3.6-4.5	4.5-4.8	4.8-5.1	5.1-5.3	5.3-5.5	5.5-5.7	5.7-6.0	6.0-6.2	6.2-6.3	6.3-6.6	6.6-7.0	7.0-7.2

<u>Month</u>	<u>Number of Occurrences</u>											
Jan	1											
Feb	2	1										
Mar	2	1						1				1
Apr	3	1	1			1						
May	3	1			1			1				
Jun	3		1									
Jul	3											
Aug	2											
Sep	2				1							
Oct	2		1									
Nov	2	1										
Dec	2											

Note: Estimated from data prepared by Clark and Flohr.

Table 4

WIND-WAVE ANALYSIS

STORMS OCCURRING DURING A TYPICAL YEAR; WAVES FROM SOUTHEAST, SOUTH AND SOUTHWEST DIRECTIONS

Wave Ht, ft	2-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
Wave Per, sec	2.8-3.8	3.8-4.1	4.1-4.4	4.4-4.6	4.6-5.0	5.0-5.4	5.4-5.9	5.9-6.4	6.4-6.9

<u>Month</u>	<u>Number of Occurrences</u>	
Jan	3	
Feb	3	
Mar	2	1
Apr	2	1
May	2	1
Jun	2	
Jul	2	
Aug	2	
Sep	3	
Oct	3	
Nov	3	1
Dec	3	

Note: Estimated from data prepared by Clark and Flohr.

Table 5

STORM DAMAGE TO BREAKWATER SECTIONS - CU YD PER FT LENGTH OF BREAKWATER  
WAVES FROM EAST AND NORTHEAST DIRECTIONS

WAVE HEIGHT in ft	Design 1				Design 1A				Design 2				Design 2A	
	A- and B- Material Section	Repaired	Repaired	Repaired	Repaired	Repaired	A- and B- Material Section	Repaired						
		Complete Section	Complete Section	Complete Section	Complete Section	Complete Section	Material Section	Complete Section						
<u>Cu Yd per Ft Length of Breakwater</u>														
15-16	16.8	15.6	17.5	6.2	11.7	5.4	5.2	2.2	5.0	4.5	5.6	3.5		
14-15	15.7	14.0	15.5	5.9	11.2	5.1	4.8	2.0	4.7	4.3	5.0	3.5		
13-14	13.5	12.5	13.0	5.6	9.7	4.9	4.2	1.9	4.4	4.1	4.5	2.3		
12-13	11.5	10.2	10.5	5.5	7.6	4.8	3.9	1.6	4.0	3.8	4.1	2.2		
11-12	9.0	8.2	10.5	5.4	6.7	4.7	3.8	1.3	3.6	3.4	4.0	2.0		
10-11	7.3	6.8	9.7	5.3	6.1	4.6	3.7	1.1	3.1	2.9	3.9	1.5		
9-10	5.7	4.8	8.1	5.2	4.7	4.3	3.0	0.8	2.8	2.5	3.8	1.3		
8-9	5.6	4.5	7.7	5.1	4.2	3.7	2.0	0.5	2.7	2.3	3.6	1.2		
7-8	5.0	4.1	5.8	4.6	3.3	3.1	1.0	0.3	2.6	1.6	3.2	1.1		
6-7	4.4	4.0	3.9	3.2	2.7	2.6	0.2	0.0	2.5	1.4	2.8	1.0		
5-6	3.4	2.9	2.9	2.4	2.0	1.9	0.0	0.0	1.9	1.0	2.1	0.9		
4-5	2.0	1.8	1.6	1.4	1.2	1.1	0.0	0.0	1.1	0.6	1.2	0.5		
3-4	1.3	1.1	1.0	0.9	0.7	0.6	0.0	0.0	0.7	0.4	0.8	0.3		
2-3	0.6	0.4	0.5	0.4	0.4	0.3	0.0	0.0	0.3	0.2	0.2	0.2		

Notes: Prepared from model data obtained in Waterways Experiment Station wave tank and data shown on plates 21-24.

Quantities of material eroded from the A- and B-material sections of design 1A are assumed equal to those eroded from the A- and B-material sections of design 1. A similar assumption was made with respect to the A- and B-material sections of designs 2 and 2A.

Breakwater repairs are assumed unnecessary for quantities of eroded material below heavy horizontal lines.

Table 6

STORM DAMAGE TO BREAKWATER SECTIONS - CU YD PER FT LENGTH OF BREAKWATER  
 WAVES FROM SOUTHEAST, SOUTH AND SOUTHWEST DIRECTIONS

WAVE HEIGHT in ft	Design 1				Design 1A				Design 2				Design 2A	
	A- and B- Material Section		Repaired A- and B- Material Section	Complete Section	Repaired Complete Section	Repaired Complete Section	Repaired Complete Section	A- and B- Material Section	Repaired A- and B- Material Section	Complete Section	Repaired Complete Section	Repaired Complete Section	Repaired Complete Section	Repaired Complete Section
	Cu Yd per Ft Length of Breakwater													
12-13	11.5	10.2	10.5	5.5	7.6	4.8	3.9	1.6	4.0	3.8	4.1	2.2		
11-12	9.0	8.2	10.5	5.4	6.7	4.7	3.8	1.3	3.6	3.4	4.0	2.0		
10-11	7.3	6.8	9.4	5.3	6.1	4.6	3.7	1.1	3.1	2.9	3.9	1.5		
9-10	5.4	4.3	5.8	4.4	3.8	3.5	2.2	0.6	2.5	1.9	3.2	1.3		
8-9	5.3	4.1	4.5	4.2	3.3	3.1	0.4	0.0	2.4	1.7	2.8	1.2		
7-8	5.0	3.9	4.3	3.5	2.7	2.4	0.0	0.0	2.2	1.5	2.5	1.1		
6-7	4.0	3.7	3.2	2.7	2.5	2.1	0.0	0.0	2.0	1.2	2.3	1.0		
5-6	2.5	2.1	1.6	1.3	1.4	1.2	0.0	0.0	1.2	0.7	1.4	0.8		
4-5	1.6	1.2	1.0	0.6	0.8	0.6	0.0	0.0	0.7	0.5	0.8	0.4		
3-4	0.9	0.6	0.7	0.5	0.5	0.4	0.0	0.0	0.4	0.3	0.4	0.3		
2-3	0.4	0.4	0.4	0.3	0.2	0.2	0.0	0.0	0.2	0.1	0.2	0.1		

Notes: Prepared from model data obtained in Waterways Experiment Station wave tank and data shown on plates 21-24.

Quantities of material eroded from the A- and B-material sections of design 1A are assumed equal to those eroded from the A- and B-material sections of design 1. A similar assumption was made with respect to the A- and B-material sections of designs 2 and 2A.

Breakwater repairs are assumed unnecessary for quantities of eroded materials below heavy horizontal lines.

Table 7

ESTIMATED QUANTITIES OF BREAKWATER MATERIAL REQUIRED FOR INITIAL CONSTRUCTION, MAINTENANCE DURING  
BREAKWATER CONSTRUCTION AND MAINTENANCE FOR A 40-YEAR PERIOD AFTER CONSTRUCTION

CONSTRUCTION SCHEME	(1) Material Required for Initial Construction	(2) Material Required for Maintenance During Construction	(3) Material Required for Maintenance for 40-yr Period After Construction	TOTAL (1),(2),(3)
<u>Designs 1 and 1A</u>				
A	983,400	51,000	193,600	1,228,000
B	1,117,800	48,800	150,300	1,316,900
C	1,043,800	49,300	169,500	1,262,600
<u>Designs 2 and 2A</u>				
A	983,400	14,900	83,200	1,081,500
B	1,117,800	16,600	63,300	1,197,700
C	1,043,800	15,400	61,600	1,120,800

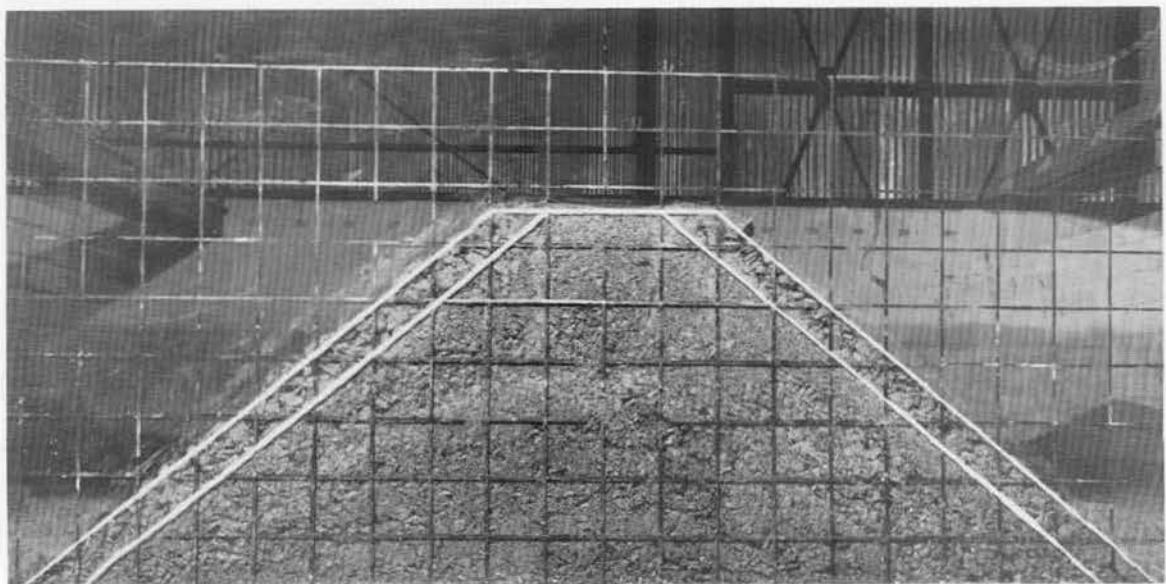
Notes: Quantities shown are the total number of cu yd required for each item.

Estimates made from data in tables 1-6.

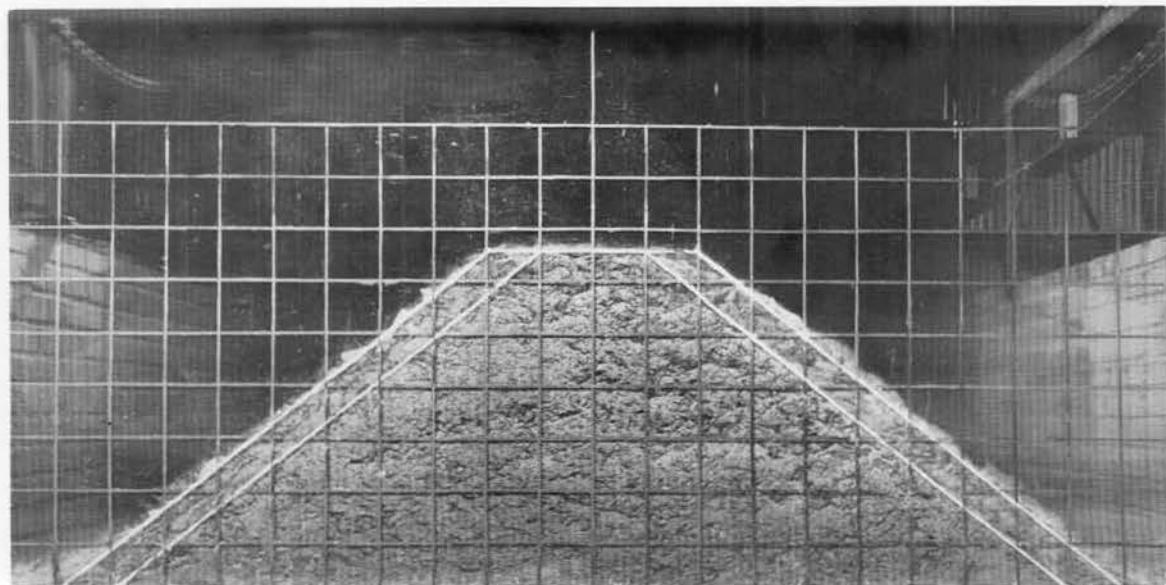
## **PHOTOGRAPHS**



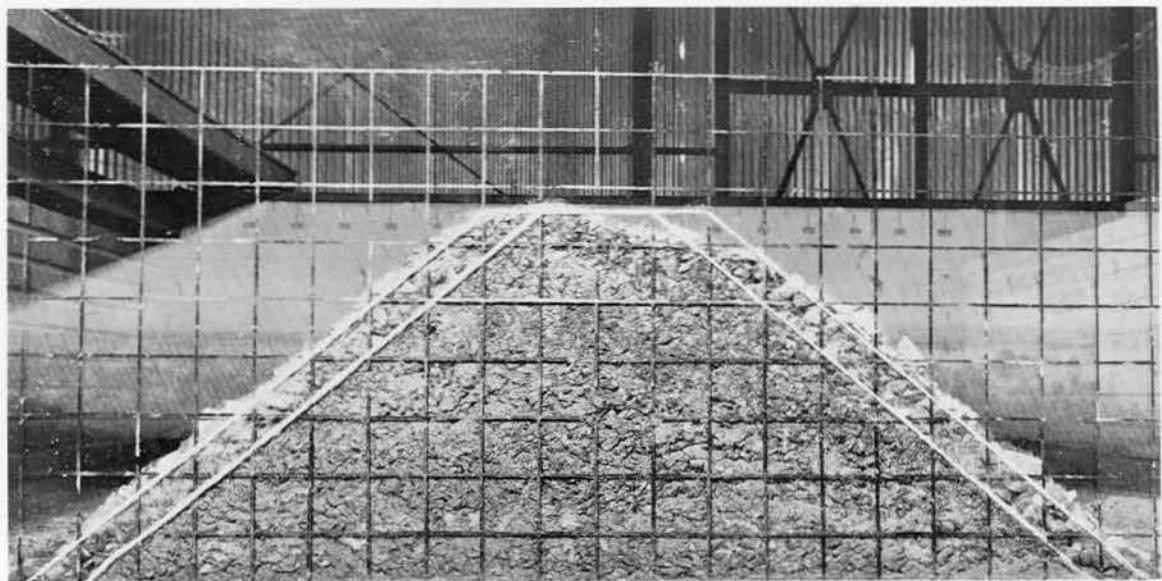
PHOTOGRAPH 1. General view of wave tank



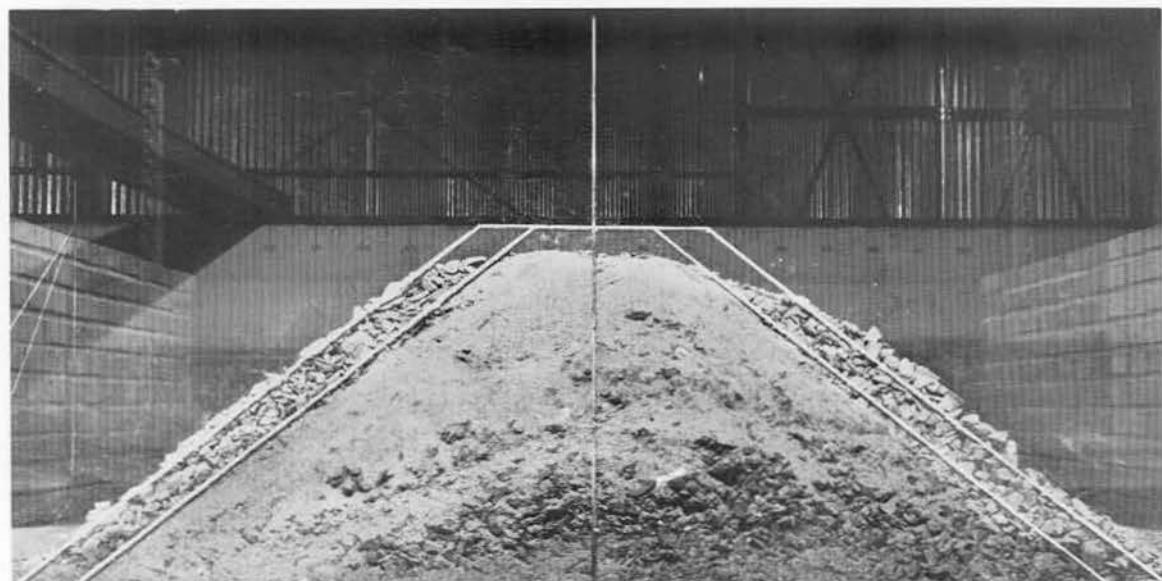
PHOTOGRAPH 2. Design 1: A- and B-material section before wave attack



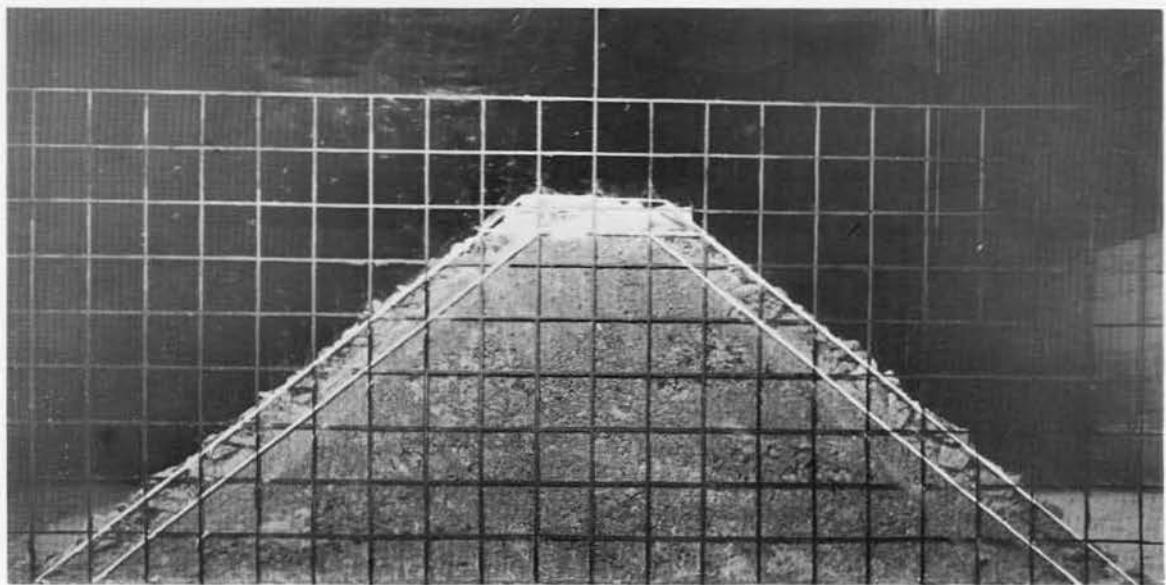
PHOTOGRAPH 3. Design 1: A- and B-material section  
after 6-ft wave attack



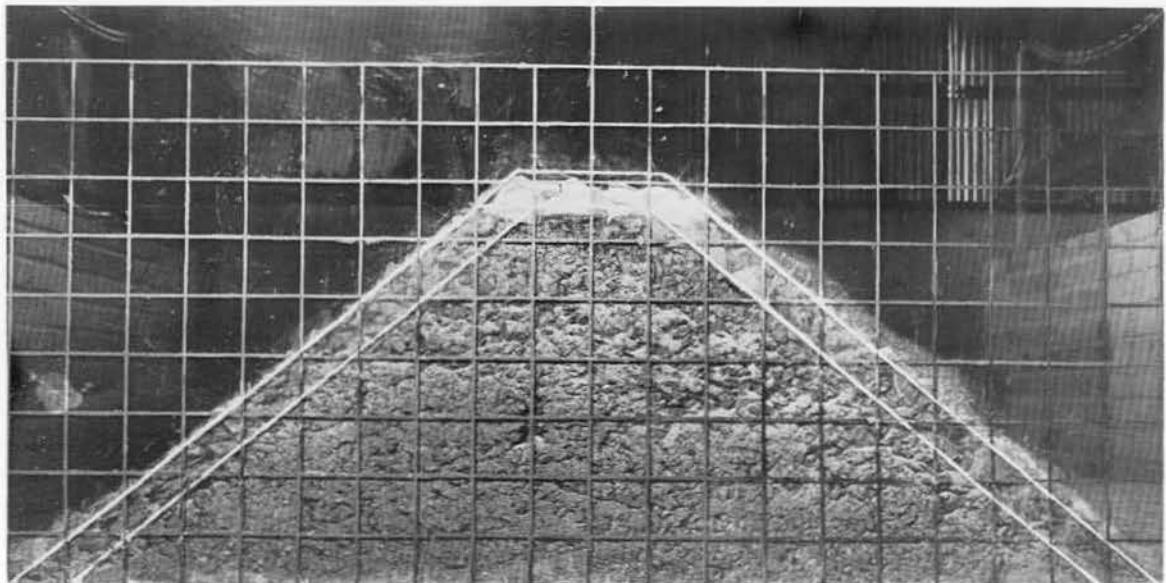
PHOTOGRAPH 4. Design 1: A- and B-material section  
after 10-ft wave attack



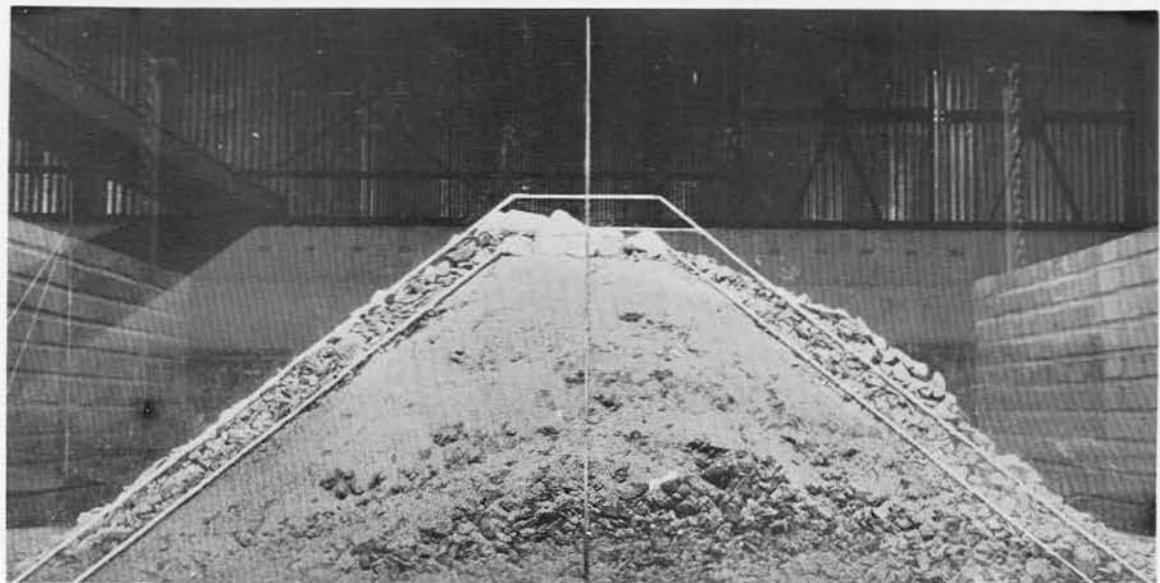
PHOTOGRAPH 5. Design 1: A- and B-material section  
after 14-ft wave attack



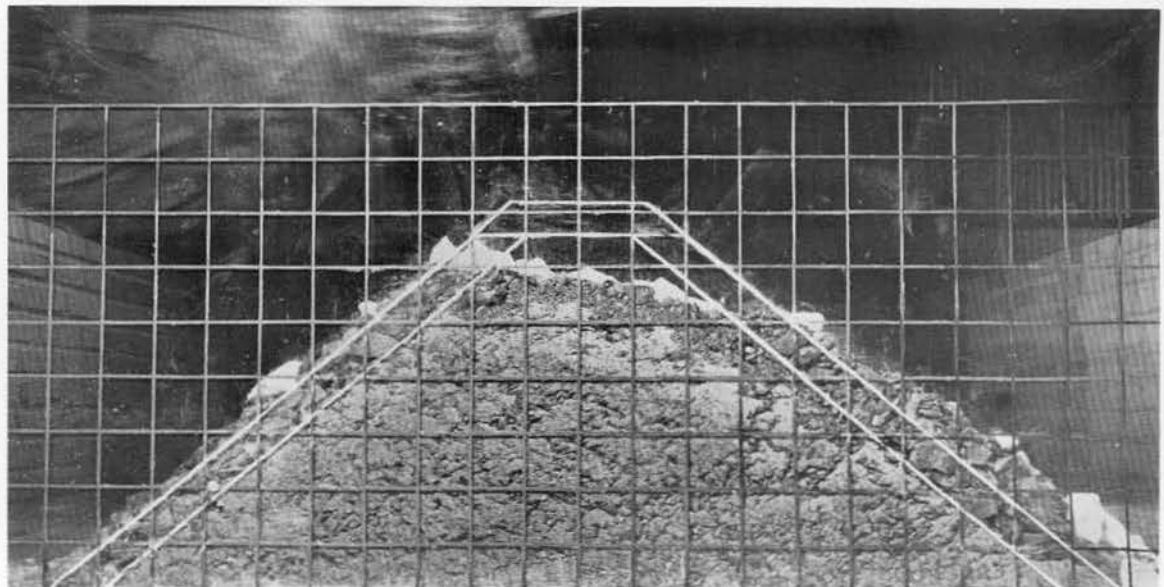
PHOTOGRAPH 6. Design 1: Complete breakwater section before wave attack



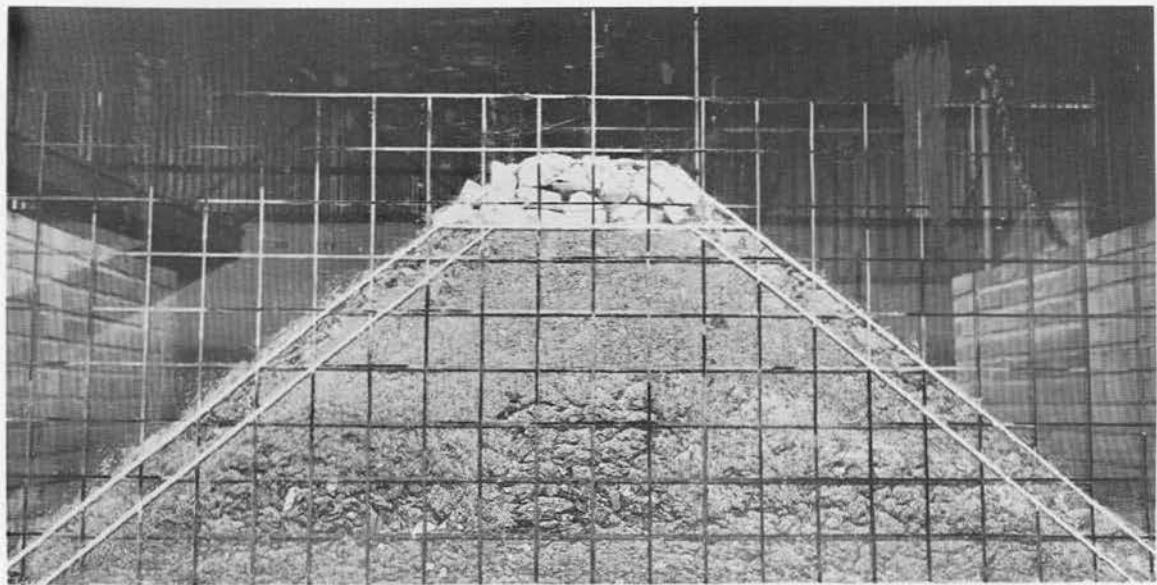
PHOTOGRAPH 7. Design 1: Complete breakwater section  
after 6-ft wave attack



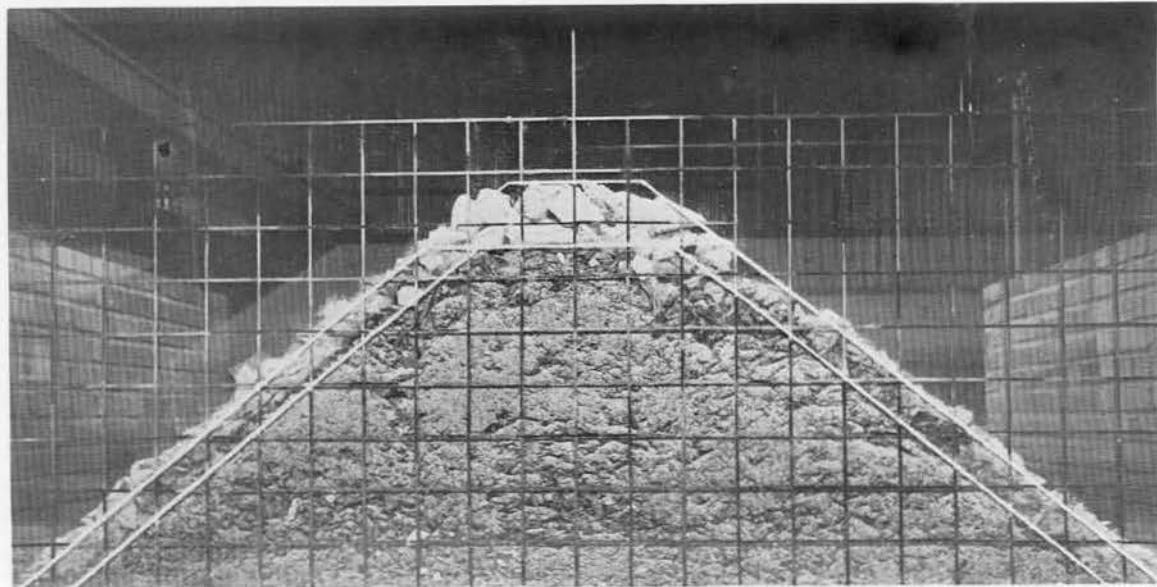
PHOTOGRAPH 8. Design 1: Complete breakwater section  
after 10-ft wave attack



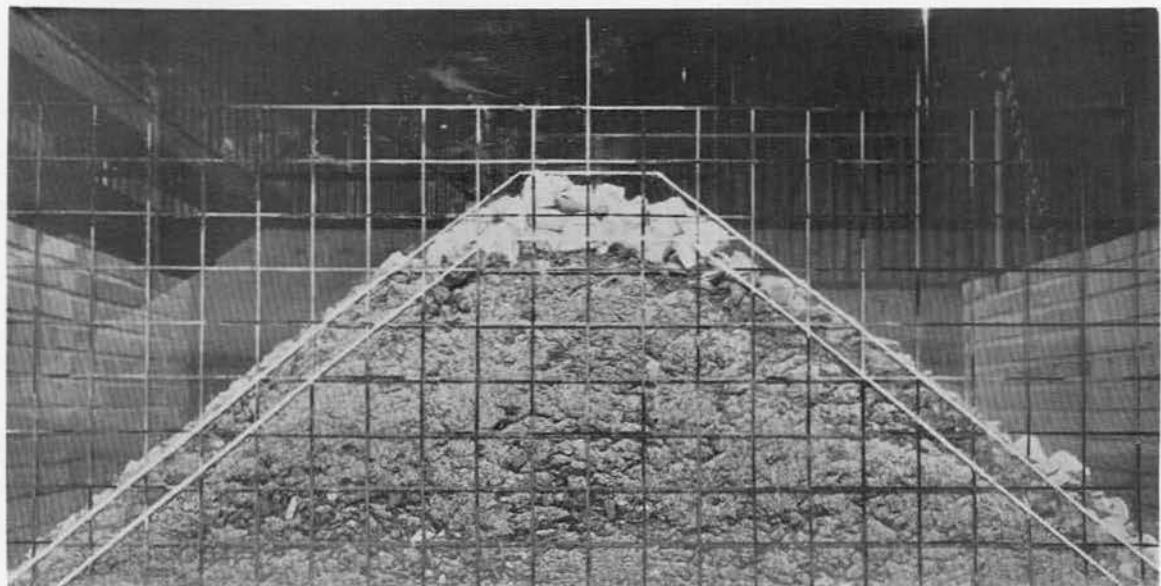
PHOTOGRAPH 9. Design 1: Complete breakwater section  
after 14-ft wave attack



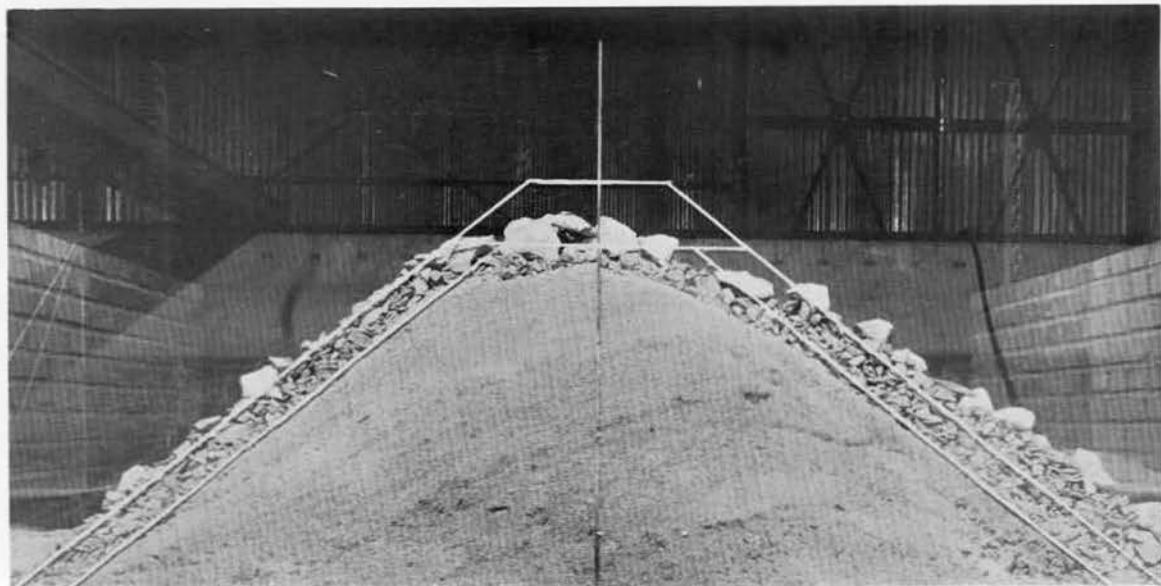
PHOTOGRAPH 10. Design 1A: Complete breakwater section  
before wave attack



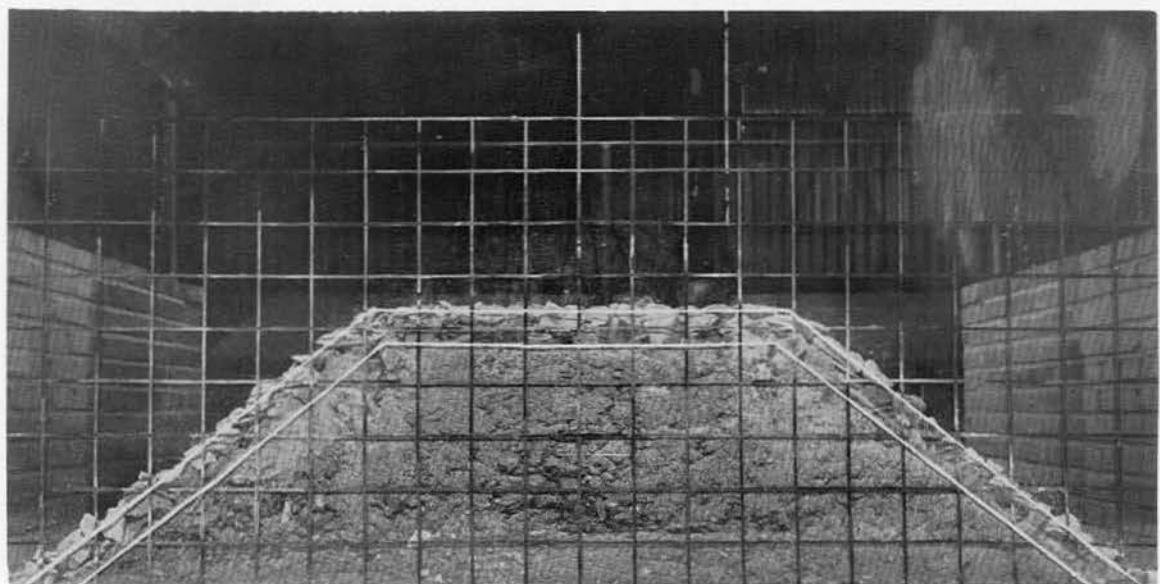
PHOTOGRAPH 11. Design 1A: Complete breakwater section  
after 6-ft wave attack



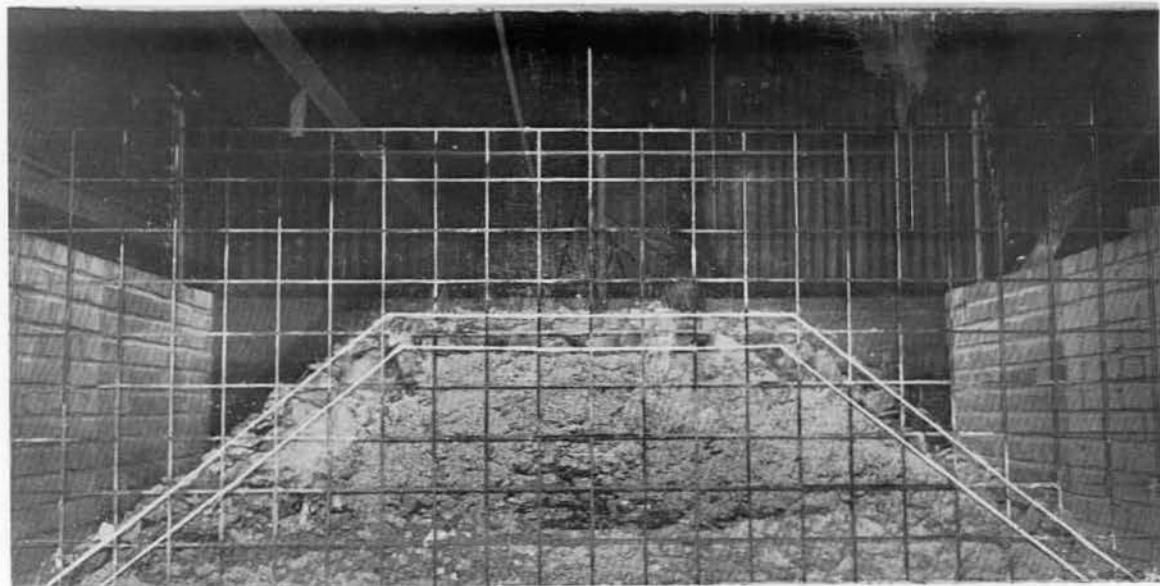
PHOTOGRAPH 12. Design 1A: Complete breakwater section  
after 10-ft wave attack



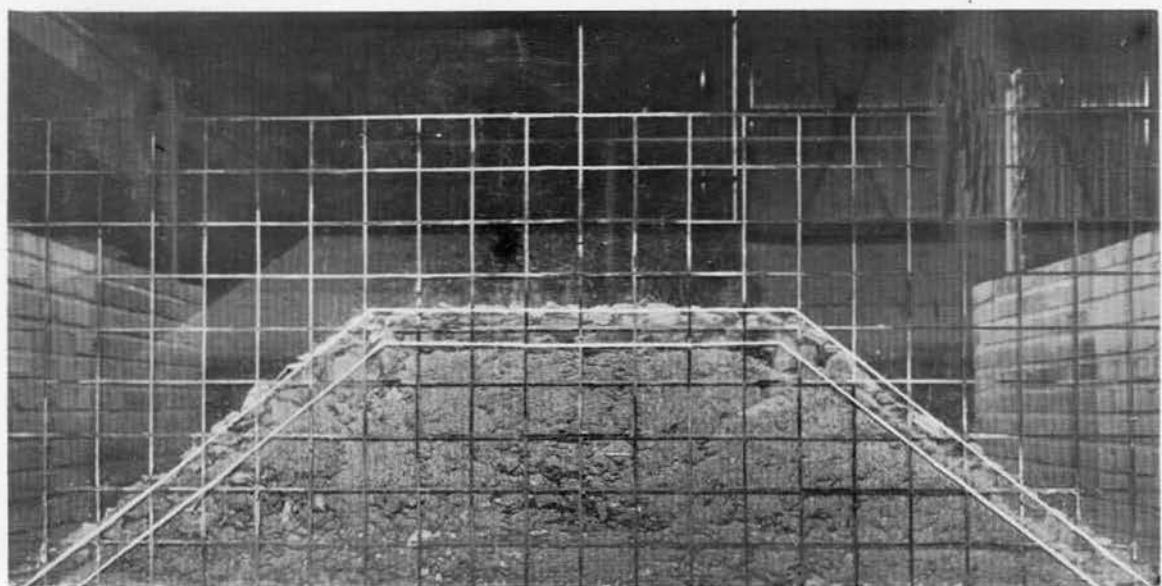
PHOTOGRAPH 13. Design 1A: Complete breakwater section  
after 14-ft wave attack



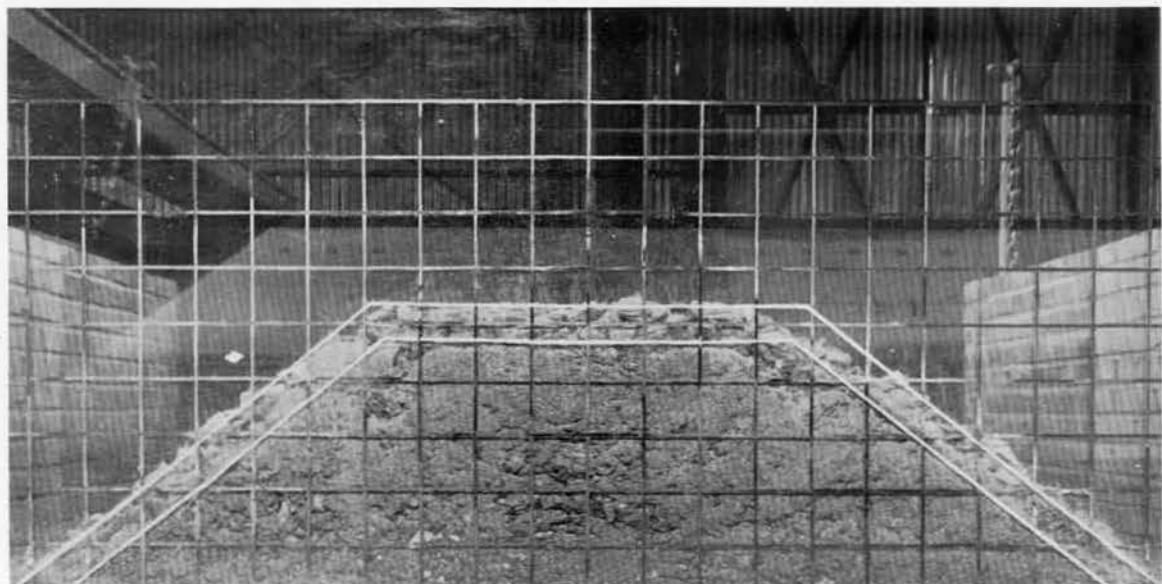
PHOTOGRAPH 14. Design 2: A- and B-material section before wave attack



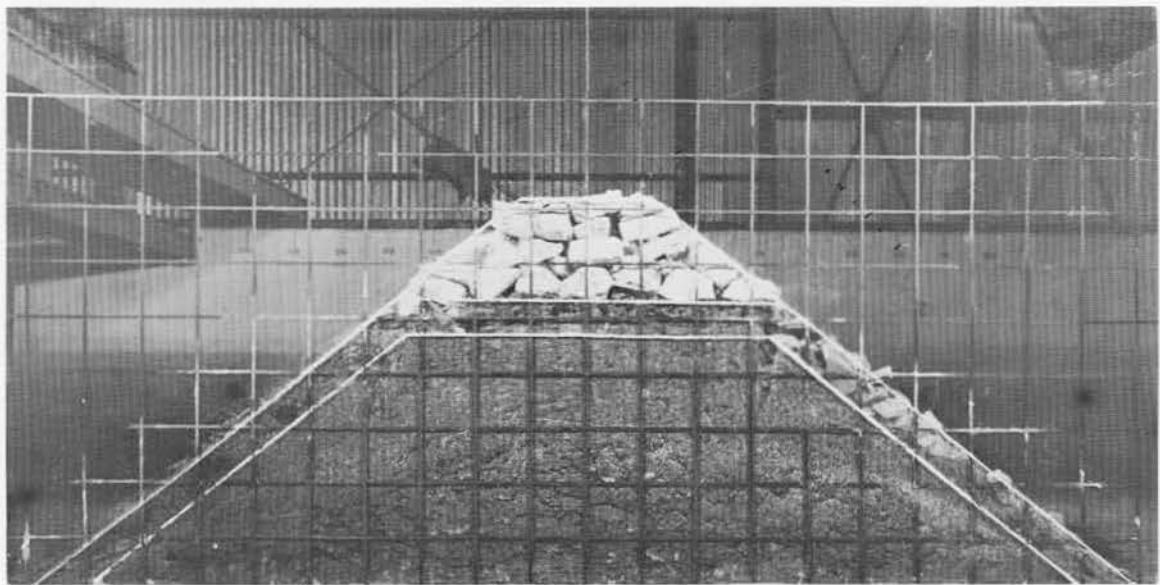
PHOTOGRAPH 15. Design 2: A- and B-material section  
after 6-ft wave attack



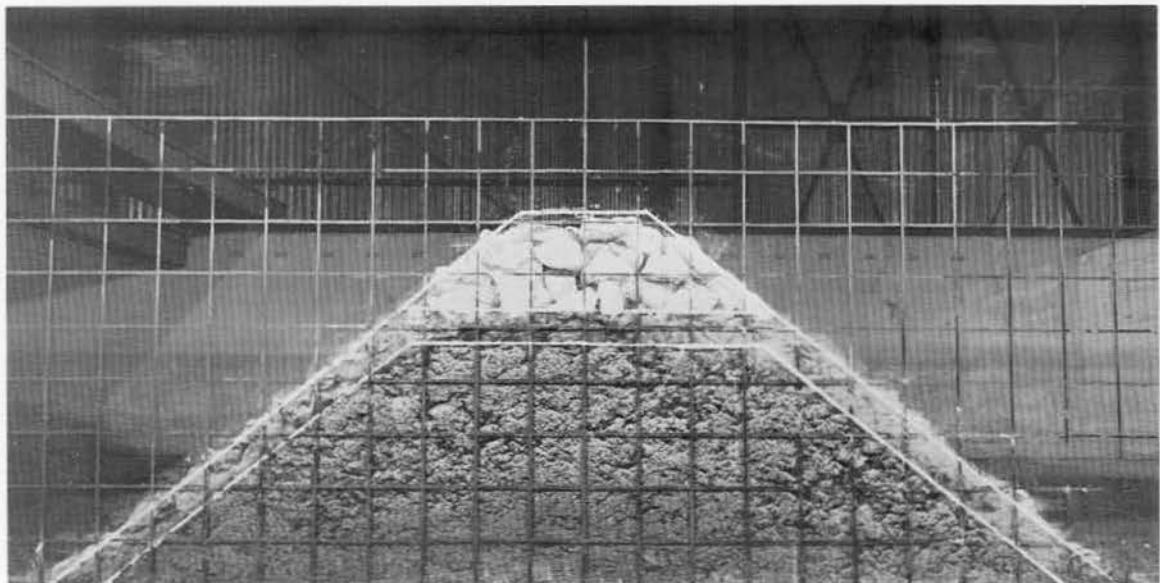
PHOTOGRAPH 16. Design 2: A- and B-material section  
after 10-ft wave attack



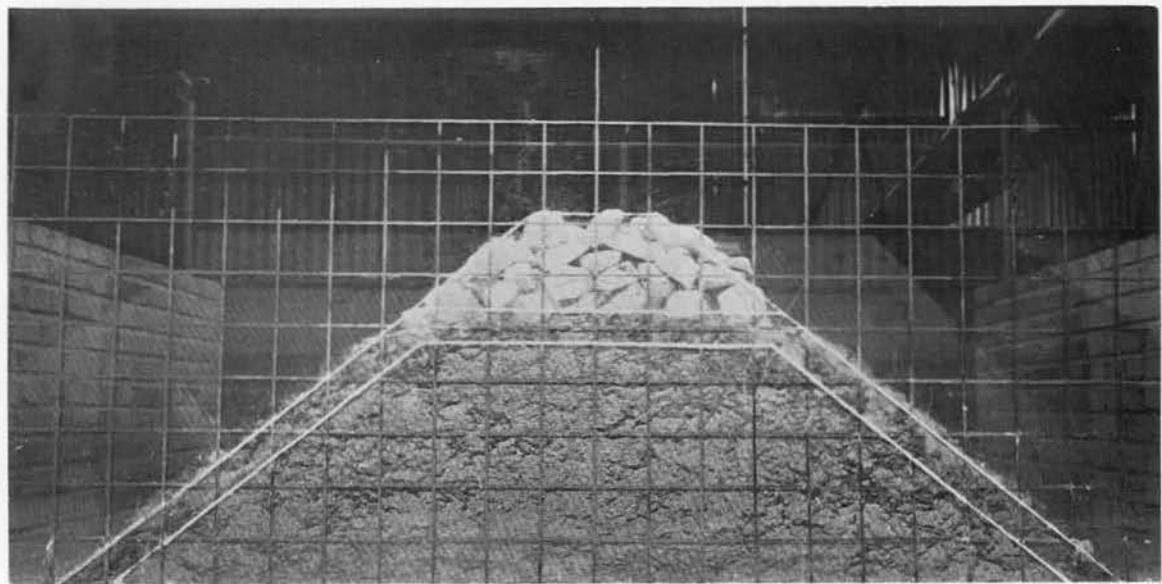
PHOTOGRAPH 17. Design 2: A- and B-material section  
after 14-ft wave attack



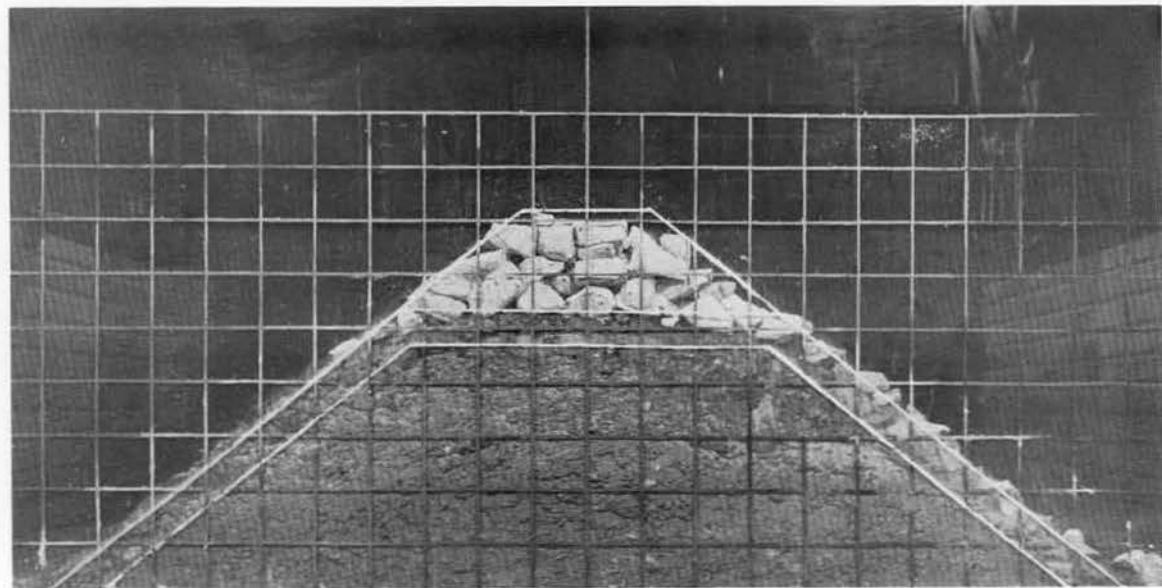
PHOTOGRAPH 18. Design 2: Complete breakwater section  
before wave attack



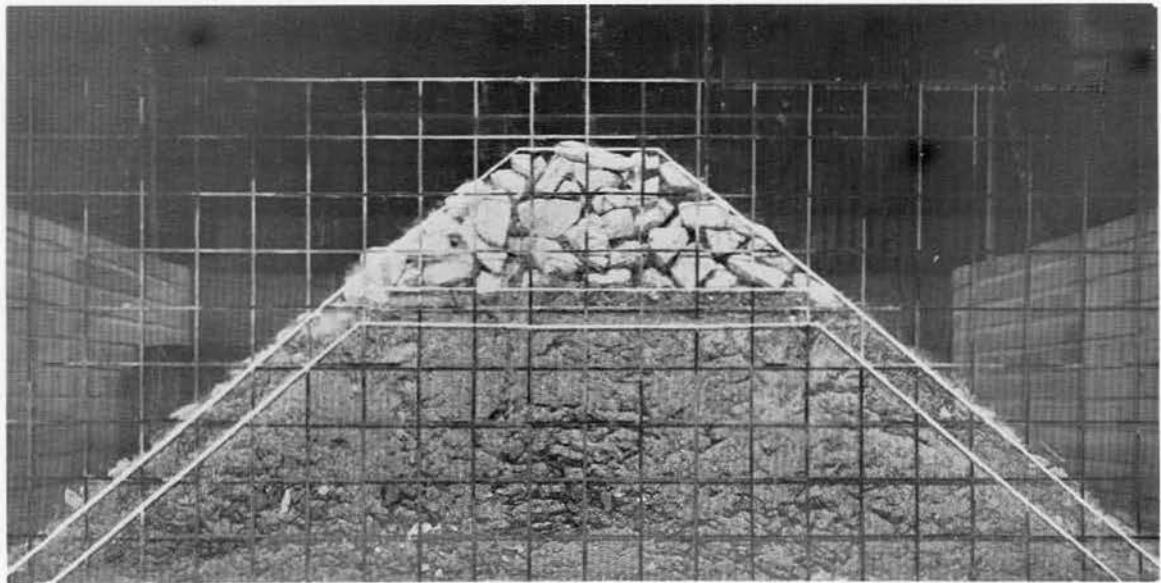
PHOTOGRAPH 19. Design 2: Complete breakwater section  
after 6-ft wave attack



PHOTOGRAPH 20. Design 2: Complete breakwater section  
after 10-ft wave attack



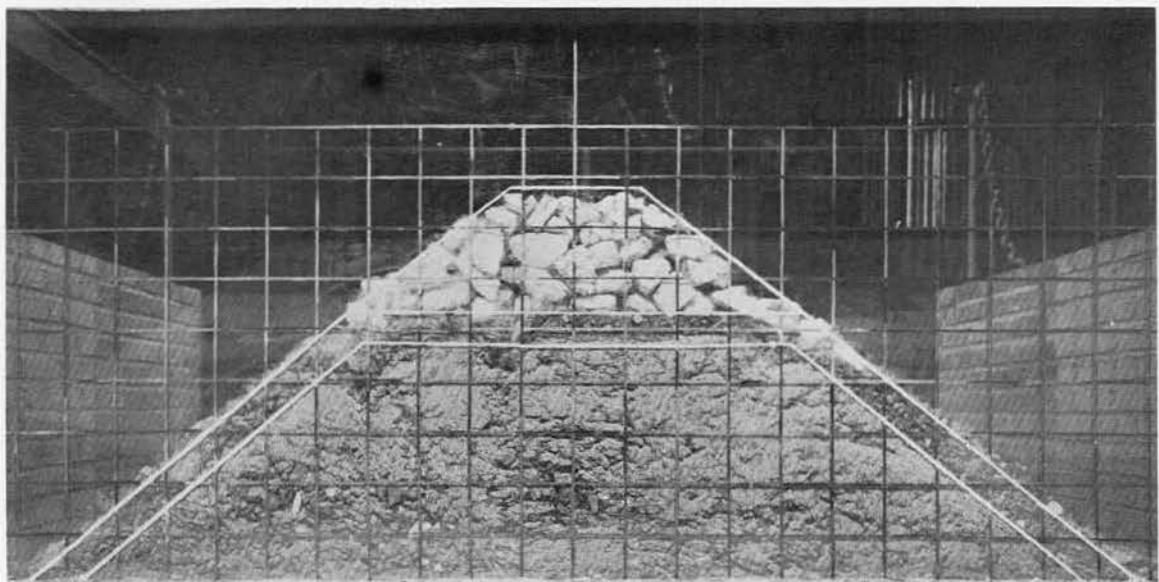
PHOTOGRAPH 21. Design 2: Complete breakwater section  
after 14-ft wave attack



PHOTOGRAPH 22. Design 2A: Complete breakwater section  
before wave attack



PHOTOGRAPH 23. Design 2A: Complete breakwater section  
after 6-ft wave attack

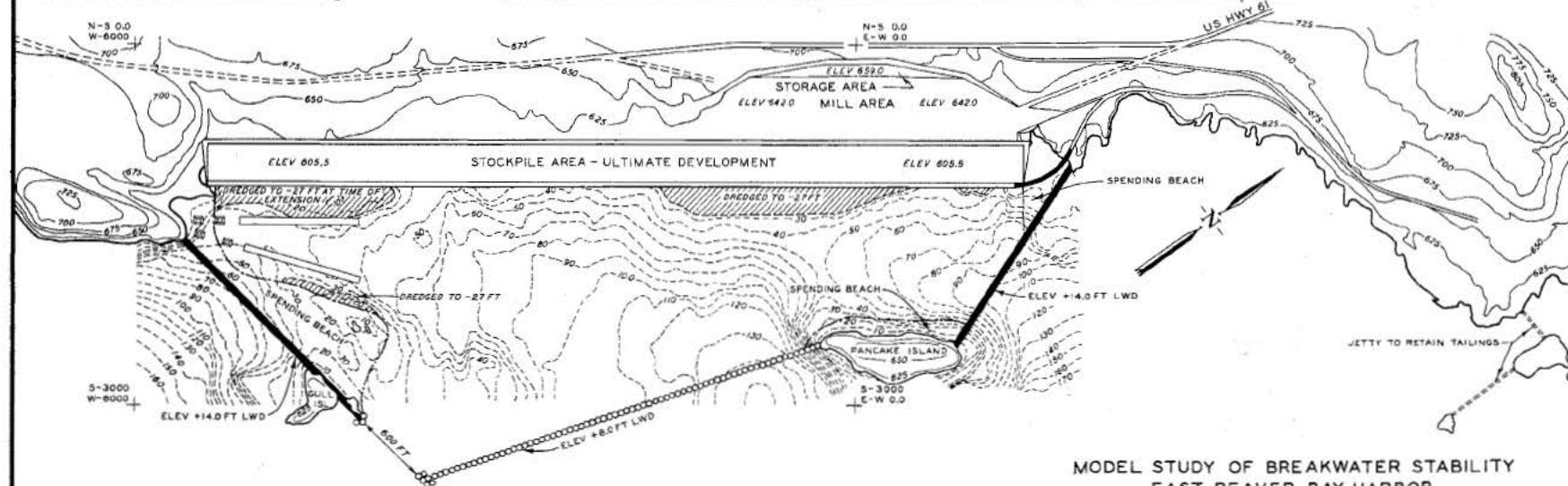
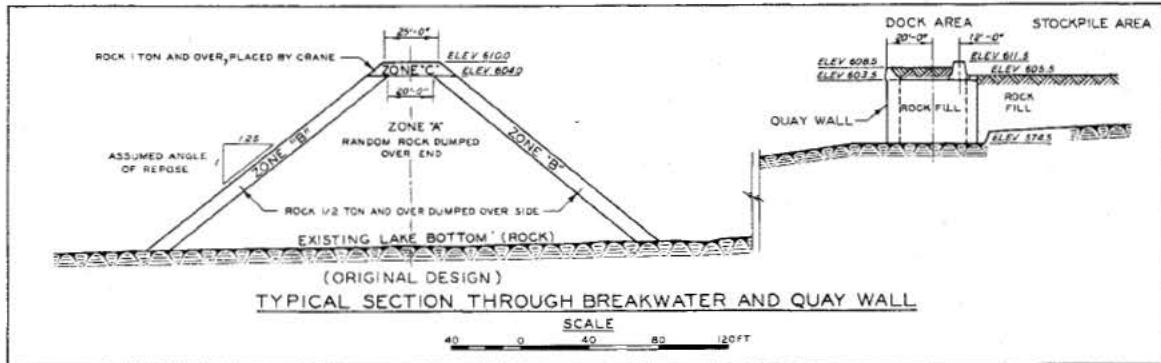


PHOTOGRAPH 24. Design 2A: Complete breakwater section after 10-ft wave attack



PHOTOGRAPH 25. Design 2A: Complete breakwater section after 14-ft wave attack

## **PLATES**



NOTE: HYDROGRAPHIC CONTOURS ARE IN FEET REFERRED  
TO LOW WATER DATUM (601.6 FT ABOVE MEAN TIDE  
AT NEW YORK CITY).

TOPOGRAPHIC CONTOURS AND ELEVATIONS ARE IN FEET REFERRED TO MEAN TIDE AT NEW YORK CITY.

PLANE COORDINATE REFERENCES ARE BASED ON ARBITRARY POINTS ESTABLISHED FOR PLANT AND BREAKWATER LAYOUT BY OGLEBAY NORTON AND CO.

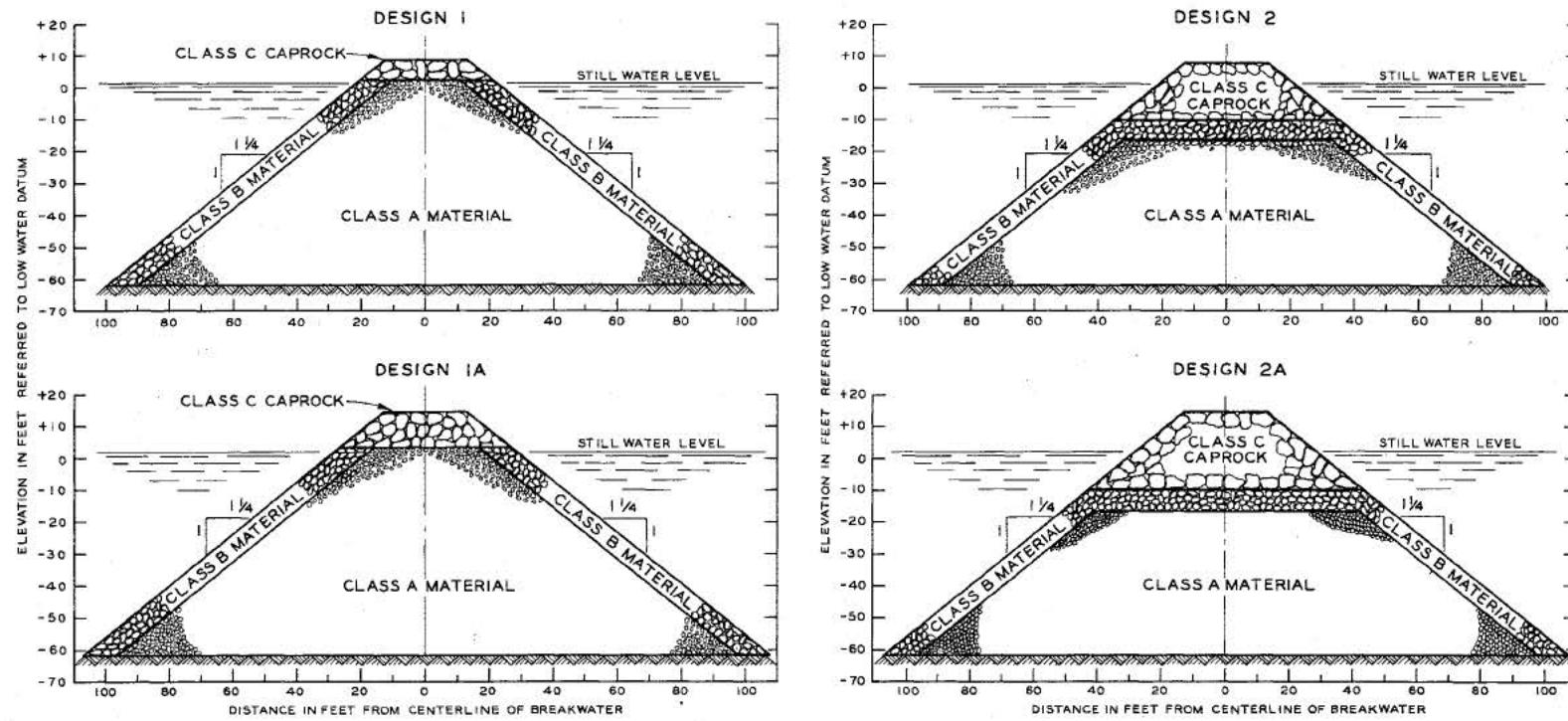
#### LEGEND

PROPOSED RUBBLE-MOUND BREAKWATER  
PROPOSED CELLULAR BREAKWATER  
LOADING PIER  
PROPOSED DREDGING. PROJECT DEPTHS AS SHOWN  
TOE OF SPENDING BEACH

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

## ELEMENTS OF PLAN-4 HARBOR DESIGN

The diagram illustrates the scale conversion between Prototype and Model dimensions. It features two horizontal bars. The top bar, labeled 'PROTOTYPE', has tick marks at 0, 500, 1000, and 1500 FT. The bottom bar, labeled 'MODEL', has tick marks at 3, 6, and 9 FT. A vertical line connects the 0 mark on the Prototype bar to the 3 mark on the Model bar, indicating a 1:500 scale ratio.



CROSS-SECTIONS AT 63 FEET WATER DEPTH

## NOTE:

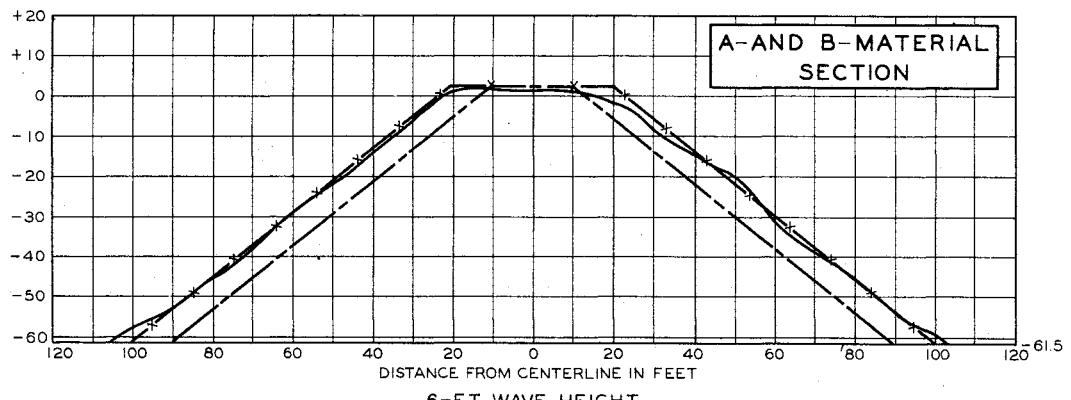
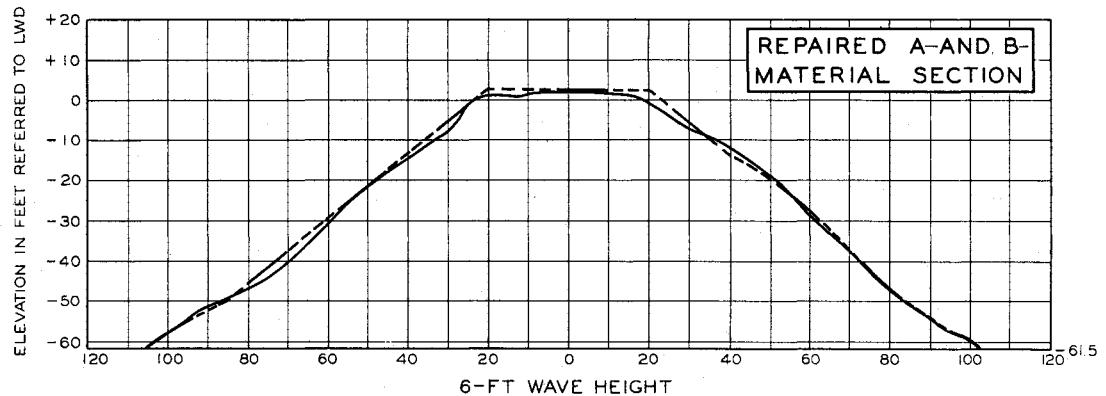
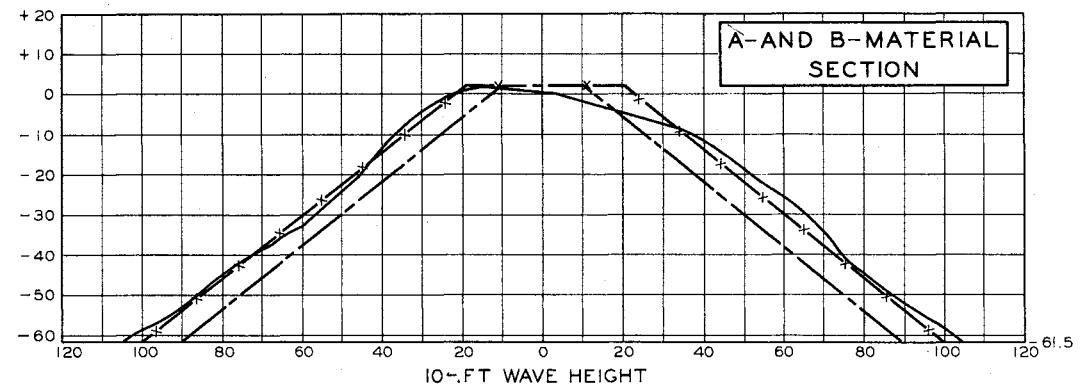
STILL WATER LEVEL = +1.5 FT LWD.

CROWN ELEVATION OF DESIGNS 1 AND 2 = +8.4 FT LWD.

CROWN ELEVATION OF DESIGNS 1A AND 2A = +14.4 FT LWD.

MODEL STUDY OF BREAKWATER STABILITY  
 EAST BEAVER BAY HARBOR  
 EAST BEAVER BAY, MINNESOTA

BREAKWATER DESIGNS 1,1A,2 AND 2A



HARBOR SIDE

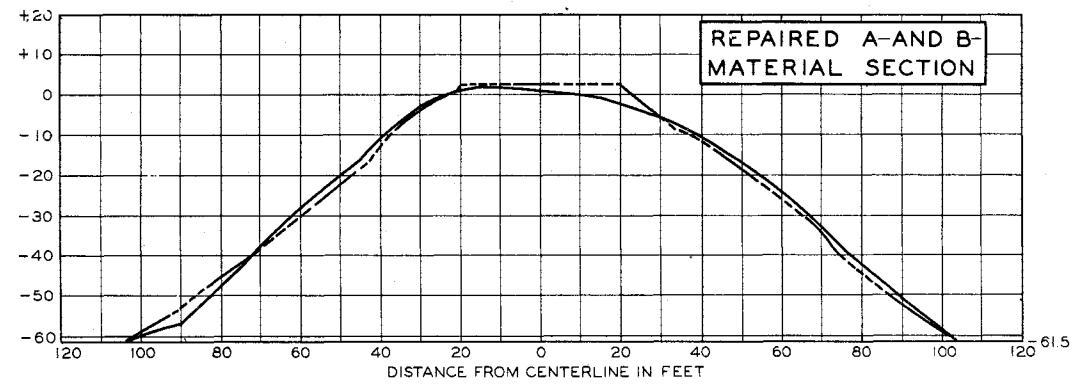
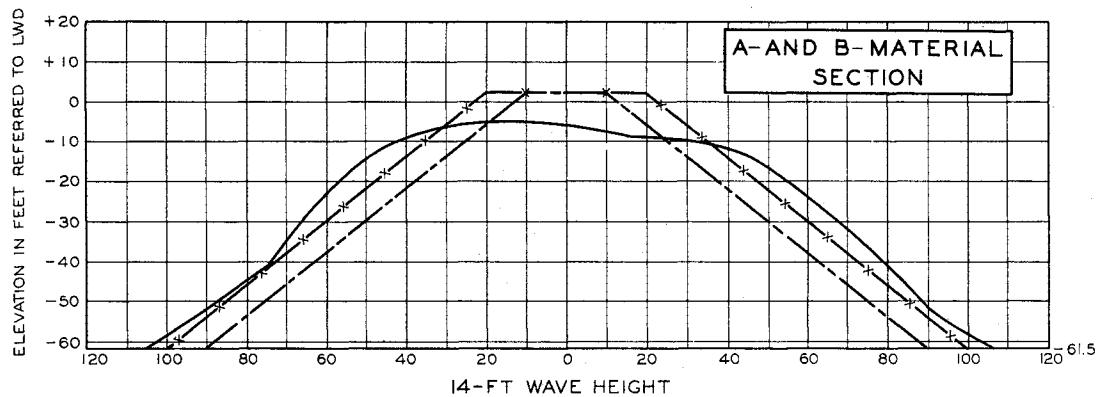
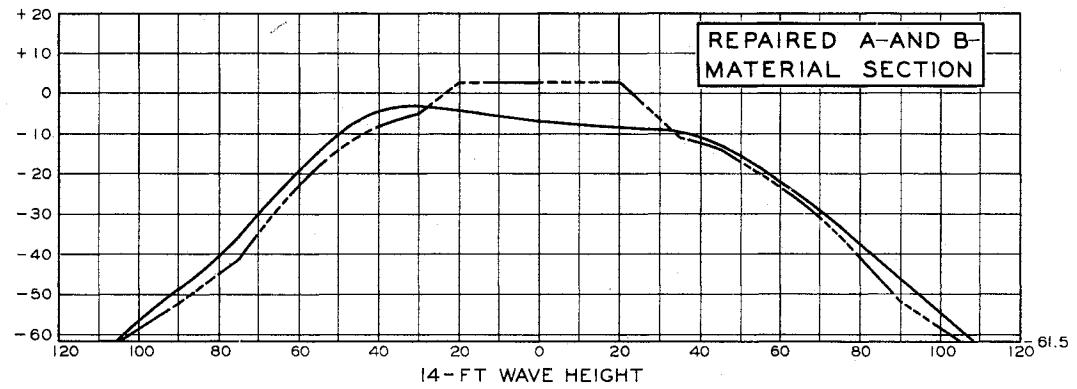
LAKE SIDE

— A-MATERIAL SECTION BEFORE WAVE ATTACK.  
X-X-X B-MATERIAL SECTION BEFORE WAVE ATTACK.  
- - - - - BREAKWATER SECTION AFTER REPAIRING,  
— STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +11.5 FT LWD.  
ALL BREAKWATER SECTIONS SUBJECT  
TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN I  
-AND B-MATERIAL SECTION



HARBOR SIDE

LAKE SIDE

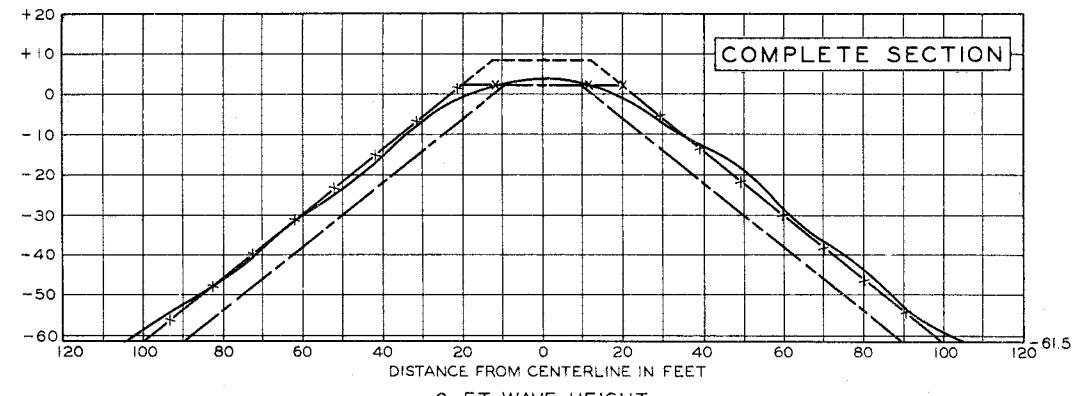
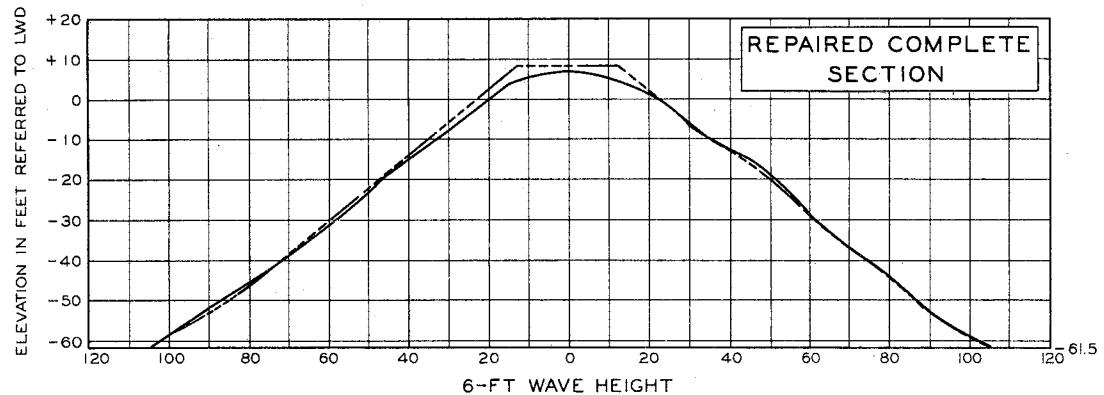
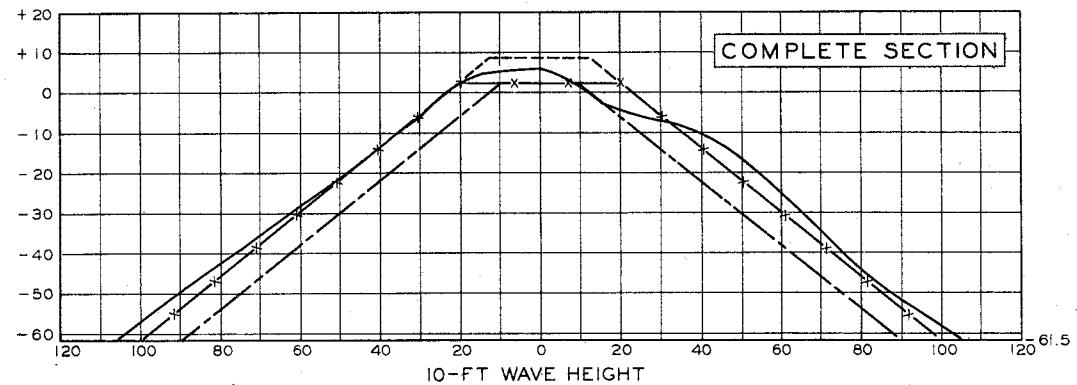
LEGEND

- — — A-MATERIAL SECTION BEFORE WAVE ATTACK.
- X — X B-MATERIAL SECTION BEFORE WAVE ATTACK
- - - - - BREAKWATER SECTION AFTER REPAIRING.
- — — STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +1.5 FT LWD.  
ALL BREAKWATER SECTIONS SUBJECT  
TO WAVE ACTION, UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN I  
A-AND B-MATERIAL SECTION



HARBOR SIDE

LAKE SIDE

LEGEND

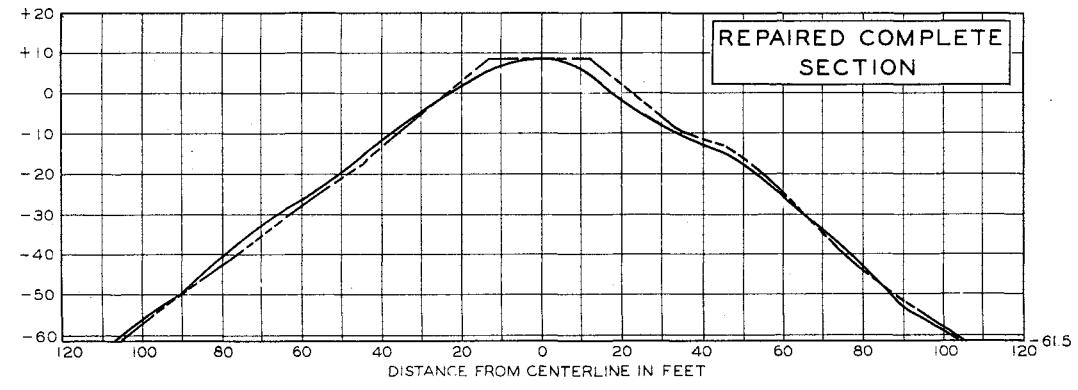
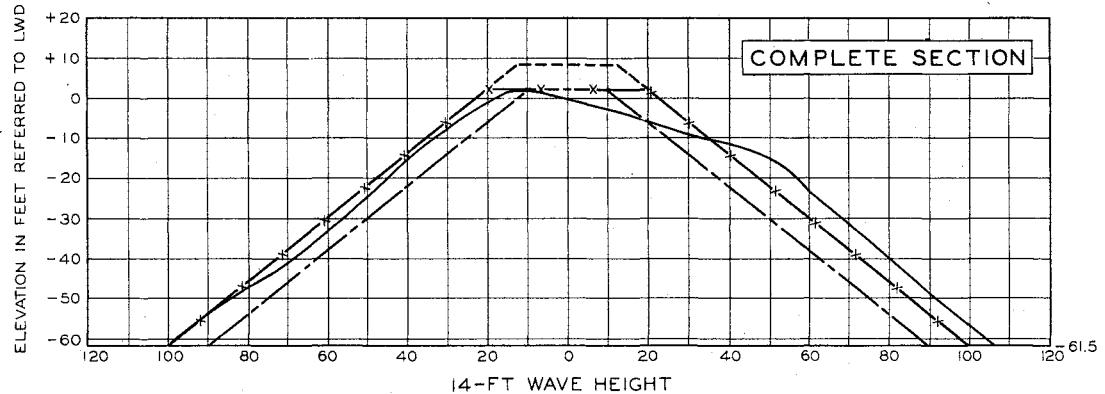
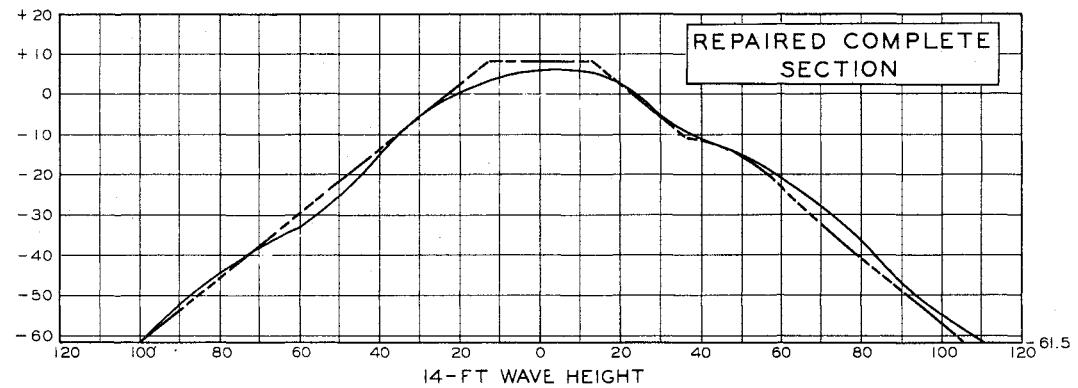
- A - MATERIAL SECTION BEFORE WAVE ATTACK.
- X — X B - MATERIAL SECTION BEFORE WAVE ATTACK.
- - - C - MATERIAL SECTION BEFORE WAVE ATTACK
- - - BREAKWATER SECTION AFTER REPAIRING.
- - - STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +1.5 FT LWL.

ALL BREAKWATER SECTIONS SUBJECTED  
TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN 1  
COMPLETE BREAKWATER SECTION



## LEGEND

— A-MATERIAL SECTION BEFORE WAVE ATTACK.  
X-X-X B-MATERIAL SECTION BEFORE WAVE ATTACK.  
— C-MATERIAL SECTION BEFORE WAVE ATTACK.  
— D-BREAKWATER SECTION AFTER REPAIRING.  
— E-STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +1.5 FT LWD.

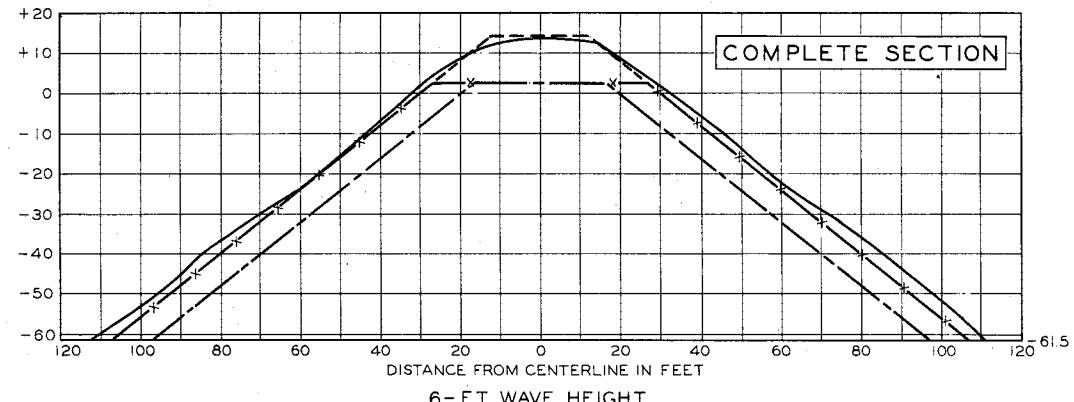
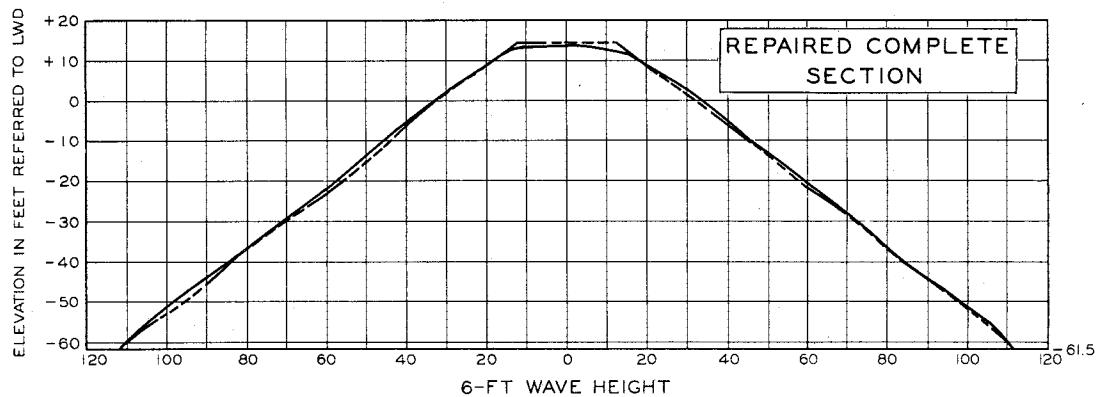
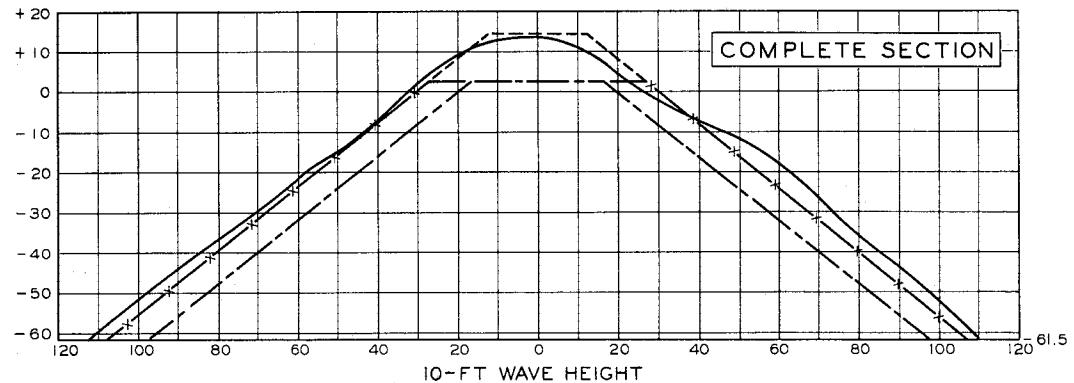
ALL BREAKWATER SECTIONS SUBJECTED  
TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR

## STABILITY TESTS

DESIGN 1

## DESIGN 1 COMPLETE BREAKWATER SECTION



HARBOR SIDE

LAKE SIDE

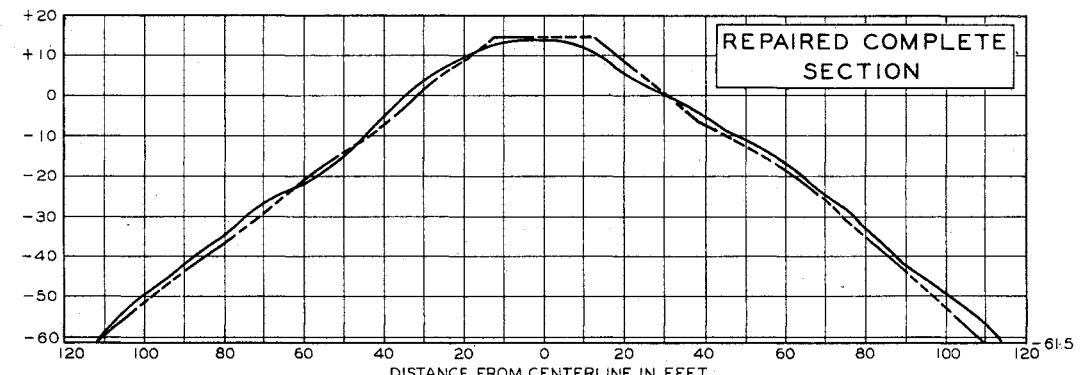
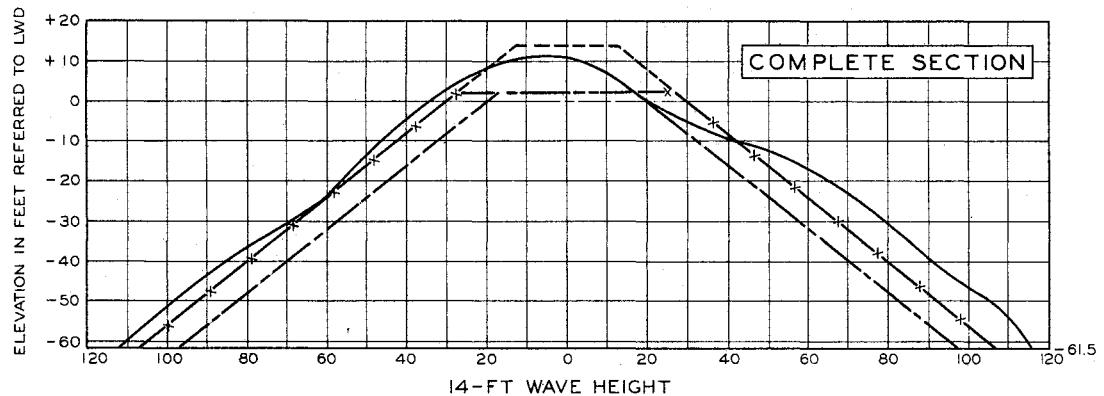
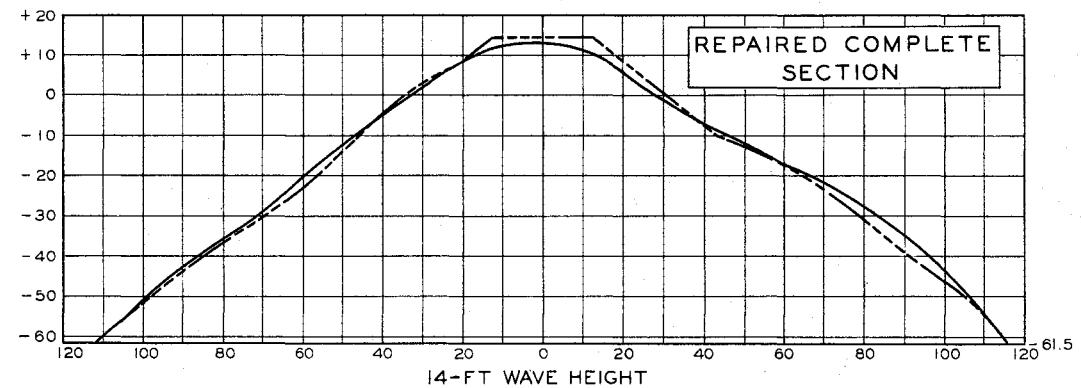
LEGEND

- A - MATERIAL SECTION BEFORE WAVE ATTACK
- X — X B - MATERIAL SECTION BEFORE WAVE ATTACK
- - C - MATERIAL SECTION BEFORE WAVE ATTACK
- - - BREAKWATER SECTION AFTER REPAIRING.
- — — STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +1.5 FT LWD.  
ALL BREAKWATER SECTIONS SUBJECT  
TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN 1A  
COMPLETE BREAKWATER SECTION



HARBOR SIDE

LAKE SIDE

LEGEND

- A - MATERIAL SECTION BEFORE WAVE ATTACK.
- x — x — B - MATERIAL SECTION BEFORE WAVE ATTACK.
- - - C - MATERIAL SECTION BEFORE WAVE ATTACK.
- - - - D - BREAKWATER SECTION AFTER REPAIRING.
- - - - E - STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +1.5 FT LWL.

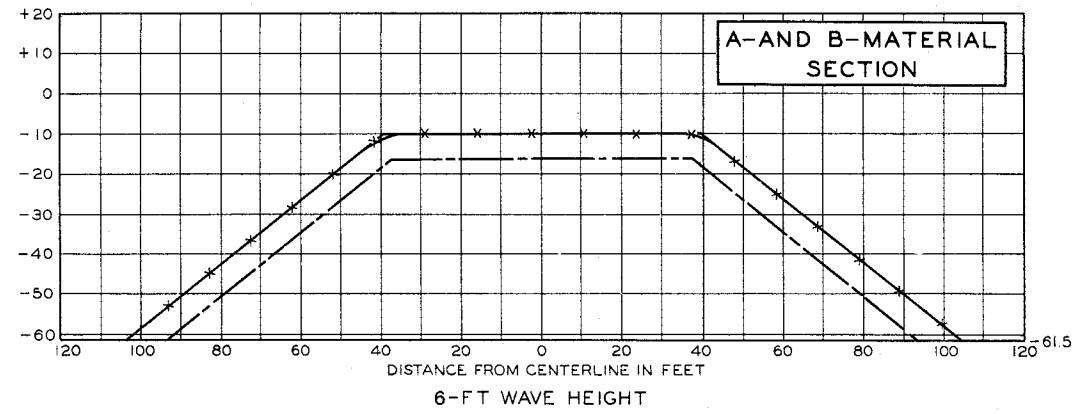
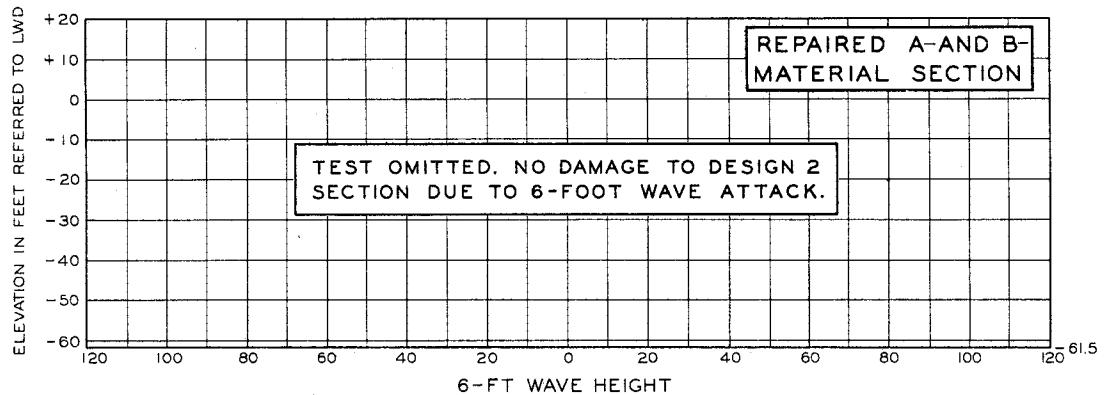
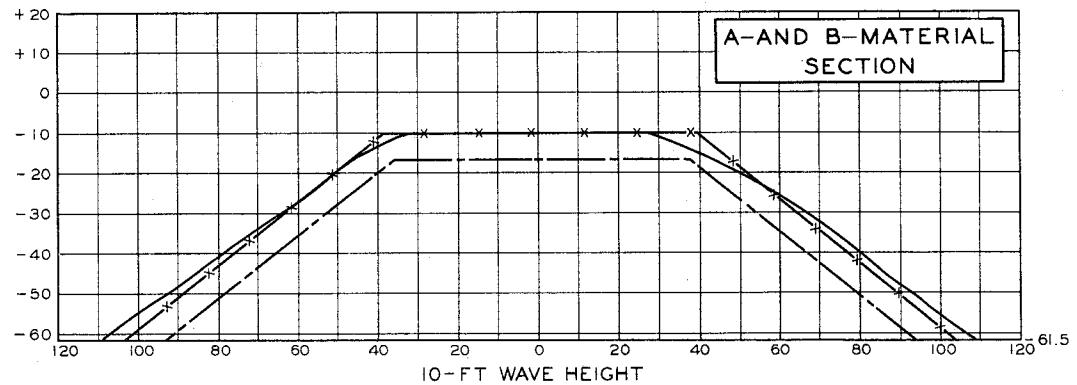
ALL BREAKWATER SECTIONS SUBJECT  
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OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STABILITY TESTS**

DESIGN 1A

COMPLETE BREAKWATER SECTION



HARBOR SIDE

LAKE SIDE

LEGEND

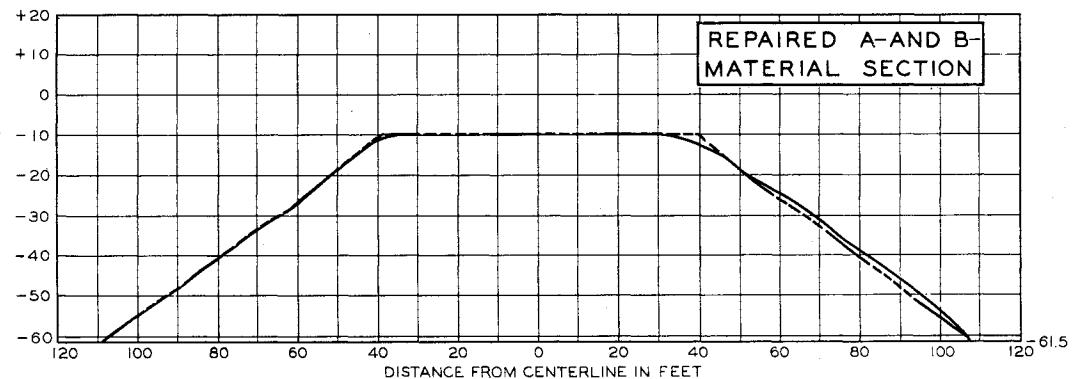
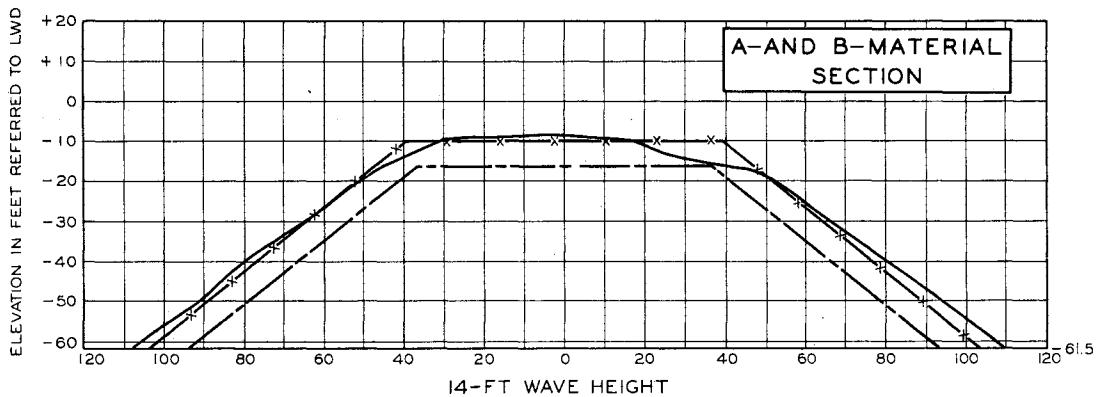
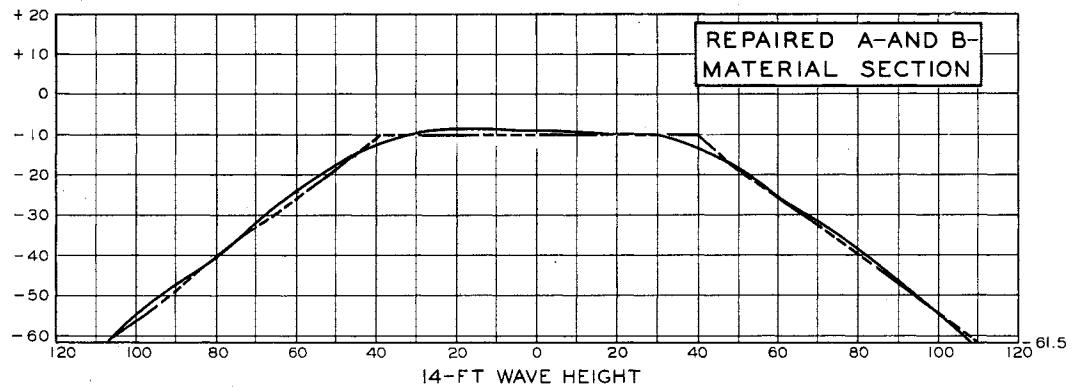
- — — A-MATERIAL SECTION BEFORE WAVE ATTACK.
- x — x B-MATERIAL SECTION BEFORE WAVE ATTACK.
- - - - - BREAKWATER SECTION AFTER REPAIRING.
- — — STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +1.5 FT LWD.

ALL BREAKWATER SECTIONS SUBJECTED  
TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN 2  
A-AND B-MATERIAL SECTION



HARBOR SIDE

LAKE SIDE

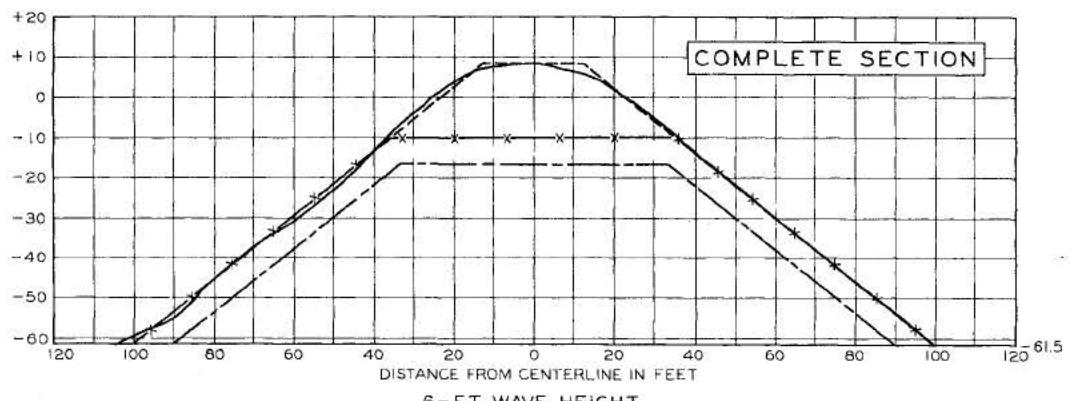
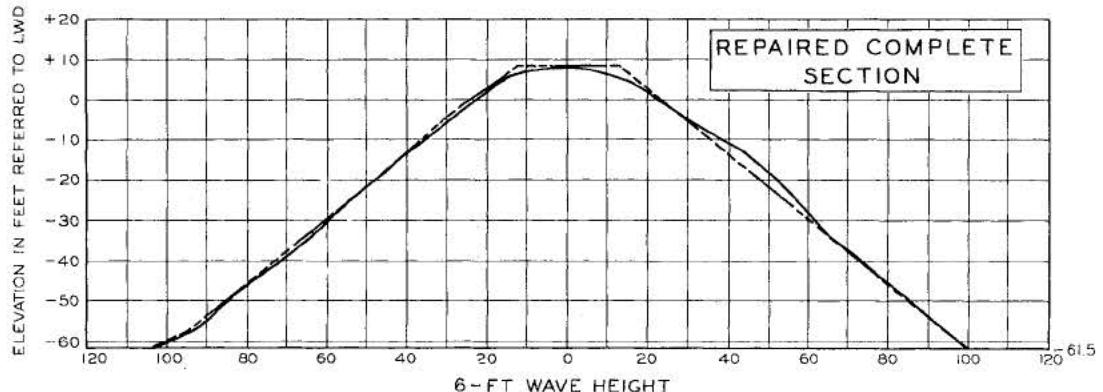
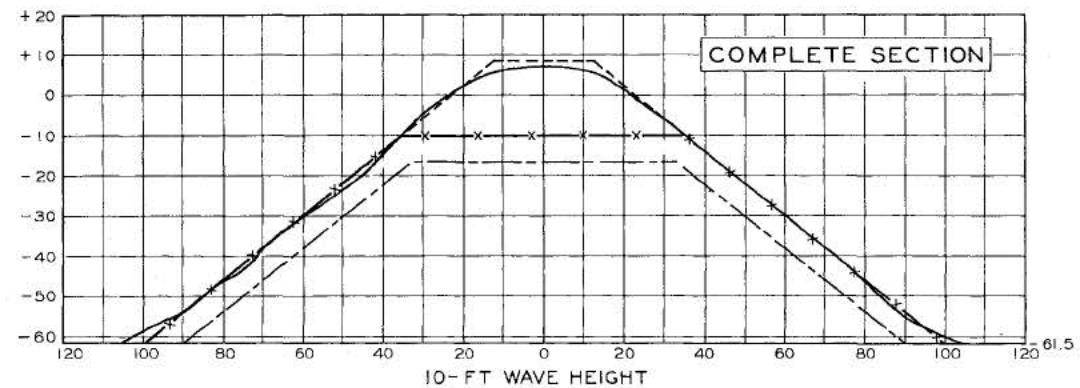
LEGEND

- A-MATERIAL SECTION BEFORE WAVE ATTACK
- X — B-MATERIAL SECTION BEFORE WAVE ATTACK
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- — — STABILIZED SECTION

NOTE: STILL-WATER LEVEL = +1.5 FT LWD.  
ALL BREAKWATER SECTIONS SUBJECT  
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OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN 2  
A-AND B-MATERIAL SECTION



HARBOR SIDE

LAKE SIDE

LEGEND

- A - MATERIAL SECTION BEFORE WAVE ATTACK
- X — X — B - MATERIAL SECTION BEFORE WAVE ATTACK
- C — C — C - MATERIAL SECTION BEFORE WAVE ATTACK
- - - - - BREAKWATER SECTION AFTER REPAIRING
- - - - - STABILIZED SECTION.

NOTE. STILL-WATER LEVEL = +1.5 FT LWD

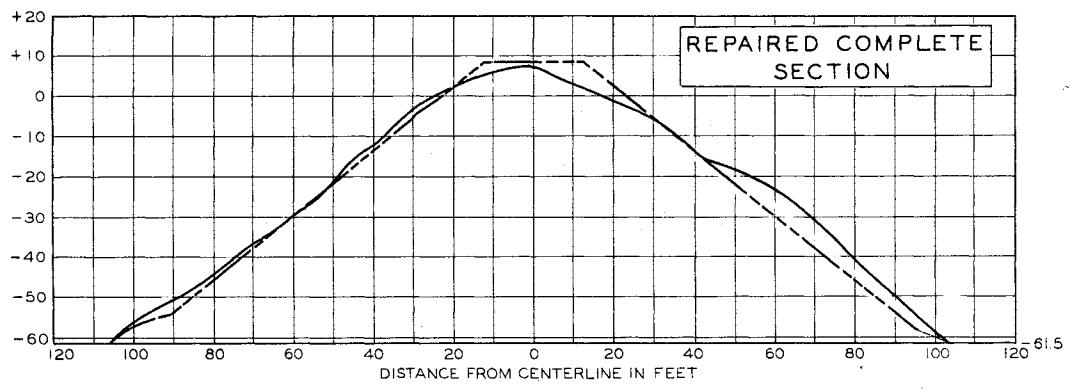
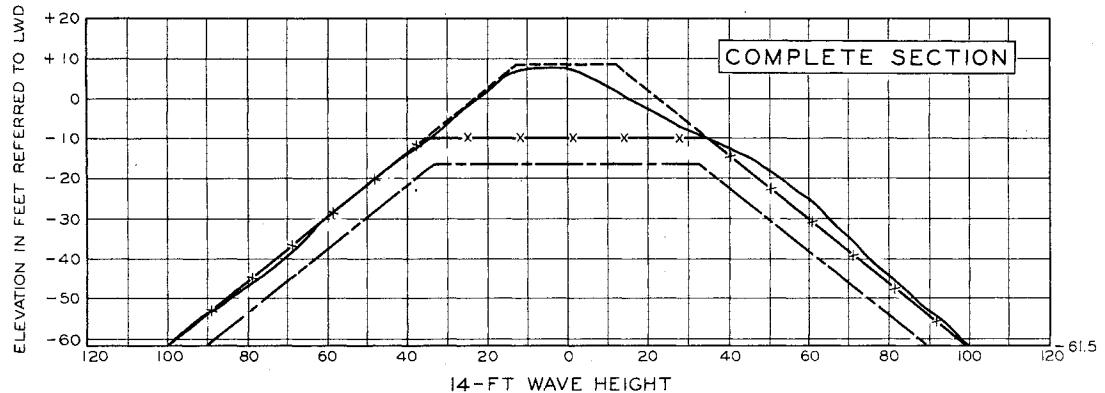
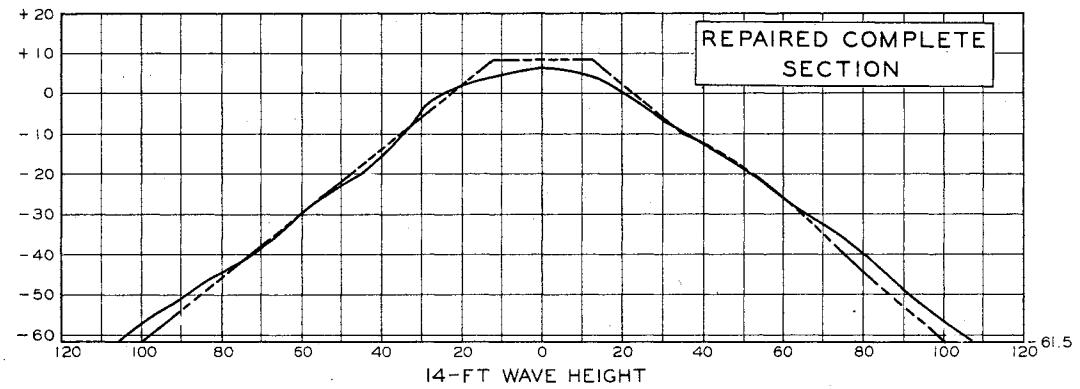
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MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STABILITY TESTS**

DESIGN 2

COMPLETE BREAKWATER SECTION



## HARBOR SIDE

## LAKE SIDE

## LEGEND

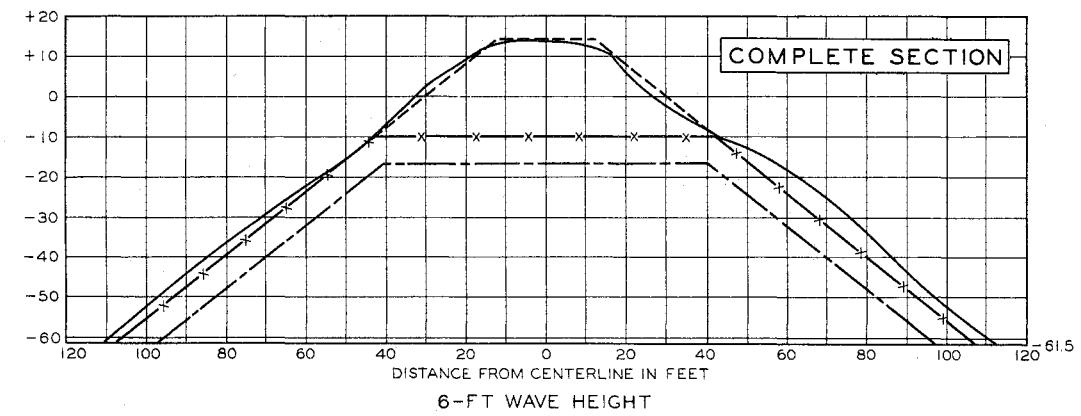
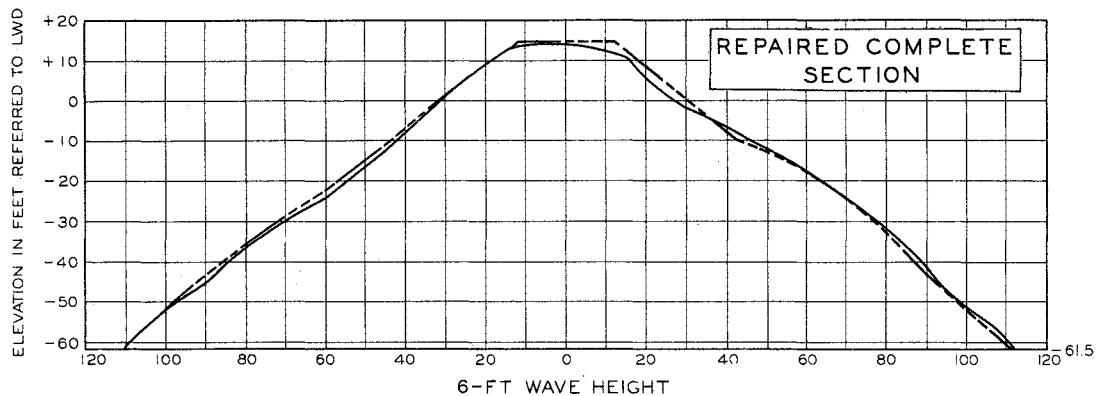
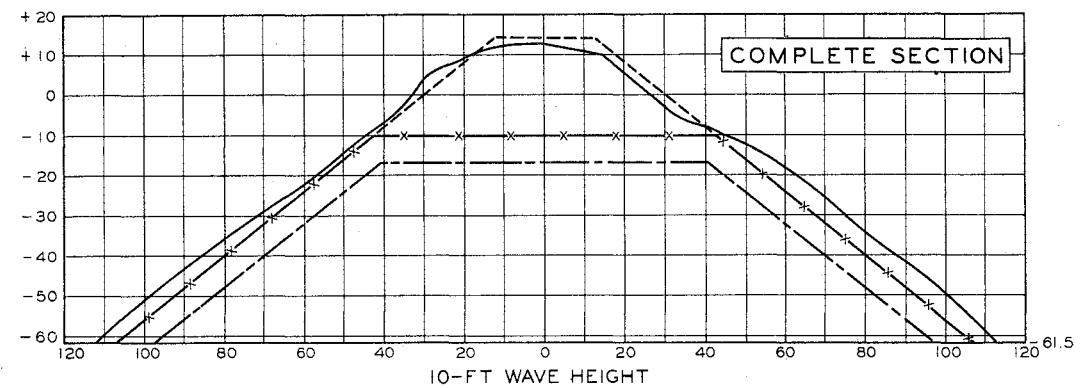
— A-MATERIAL SECTION BEFORE WAVE ATTACK.  
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— C-MATERIAL SECTION BEFORE WAVE ATTACK  
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— STABILIZED SECTION.

NOTE: STILL-WATER LEVEL = +1.5 FT LWD.

ALL BREAKWATER SECTIONS SUBJECTED  
TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN 2  
COMPLETE BREAKWATER SECTION



HARBOR SIDE

LAKE SIDE

LEGEND

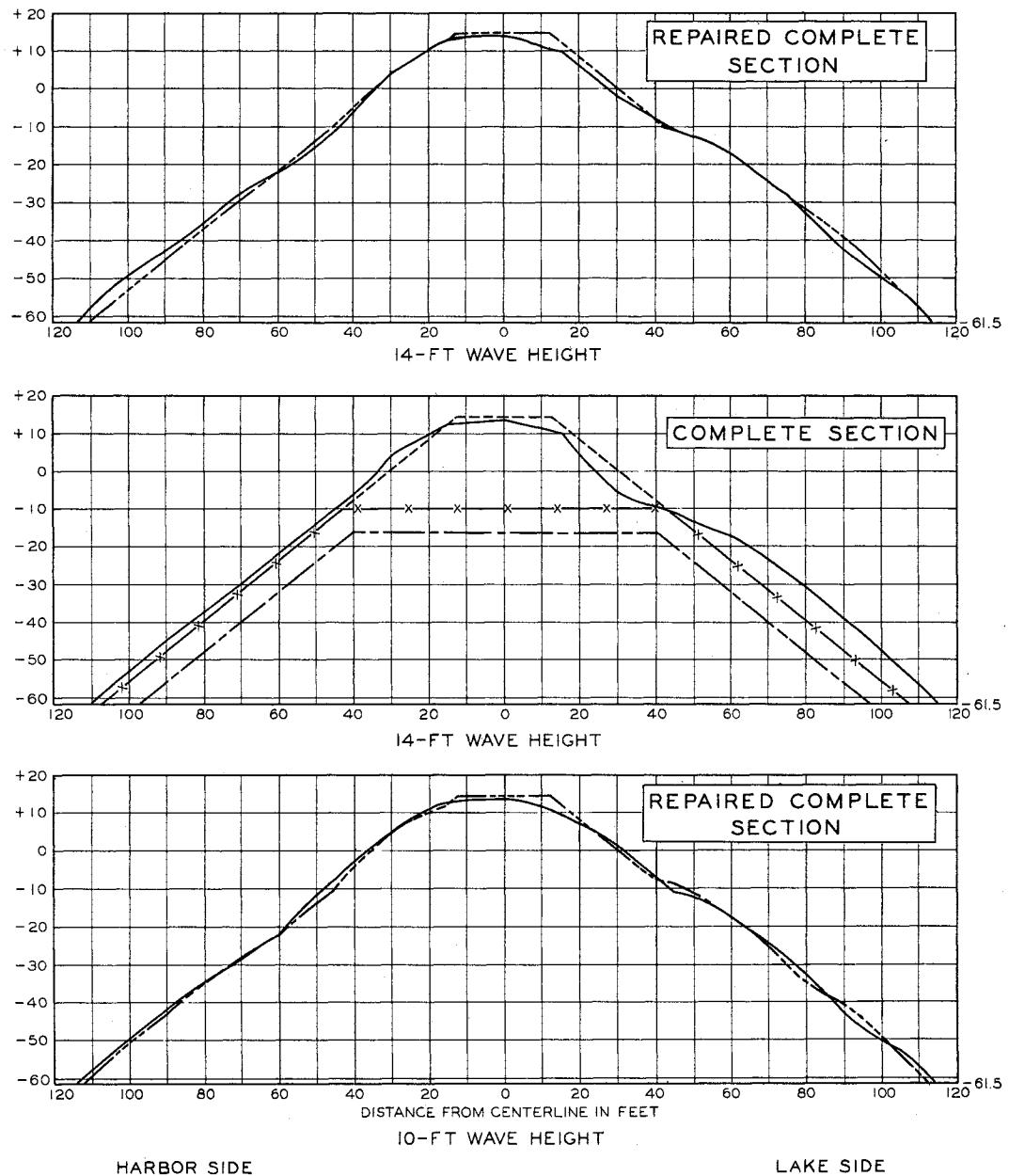
- A - MATERIAL SECTION BEFORE WAVE ATTACK
- X — X — B - MATERIAL SECTION BEFORE WAVE ATTACK
- C — C — C - MATERIAL SECTION BEFORE WAVE ATTACK
- - - - - BREAKWATER SECTION AFTER REPAIRING
- — — — — STABILIZED SECTION

NOTE: STILL-WATER LEVEL = +1.5 FT LWD.

ALL BREAKWATER SECTIONS SUBJECT  
ED TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN 2 A  
COMPLETE BREAKWATER SECTION



## LEGEND

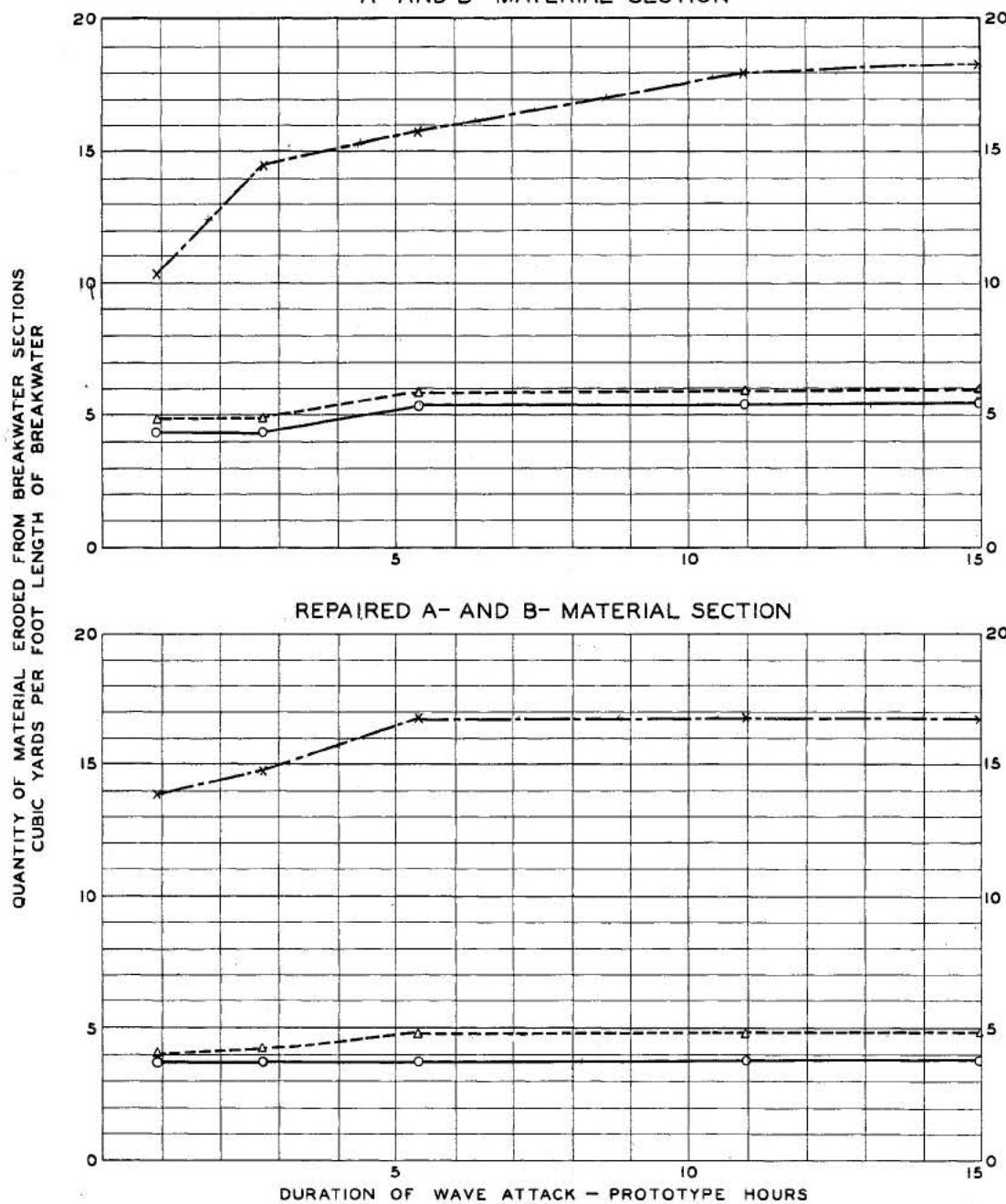
— A-MATERIAL SECTION BEFORE WAVE ATTACK.  
X—X—X B-MATERIAL SECTION BEFORE WAVE ATTACK.  
— C-MATERIAL SECTION BEFORE WAVE ATTACK  
— BREAKWATER SECTION AFTER REPAIRING  
— STABILIZED SECTION

NOTE: STILL-WATER LEVEL = +11.5 FT LWD.  
ALL BREAKWATER SECTIONS SUBJECTTED  
TO WAVE ACTION UNTIL DISPLACEMENT  
OF BREAKWATER MATERIAL CEASED

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

STABILITY TESTS  
DESIGN 2 A  
COMPLETE BREAKWATER SECTION

A- AND B- MATERIAL SECTION



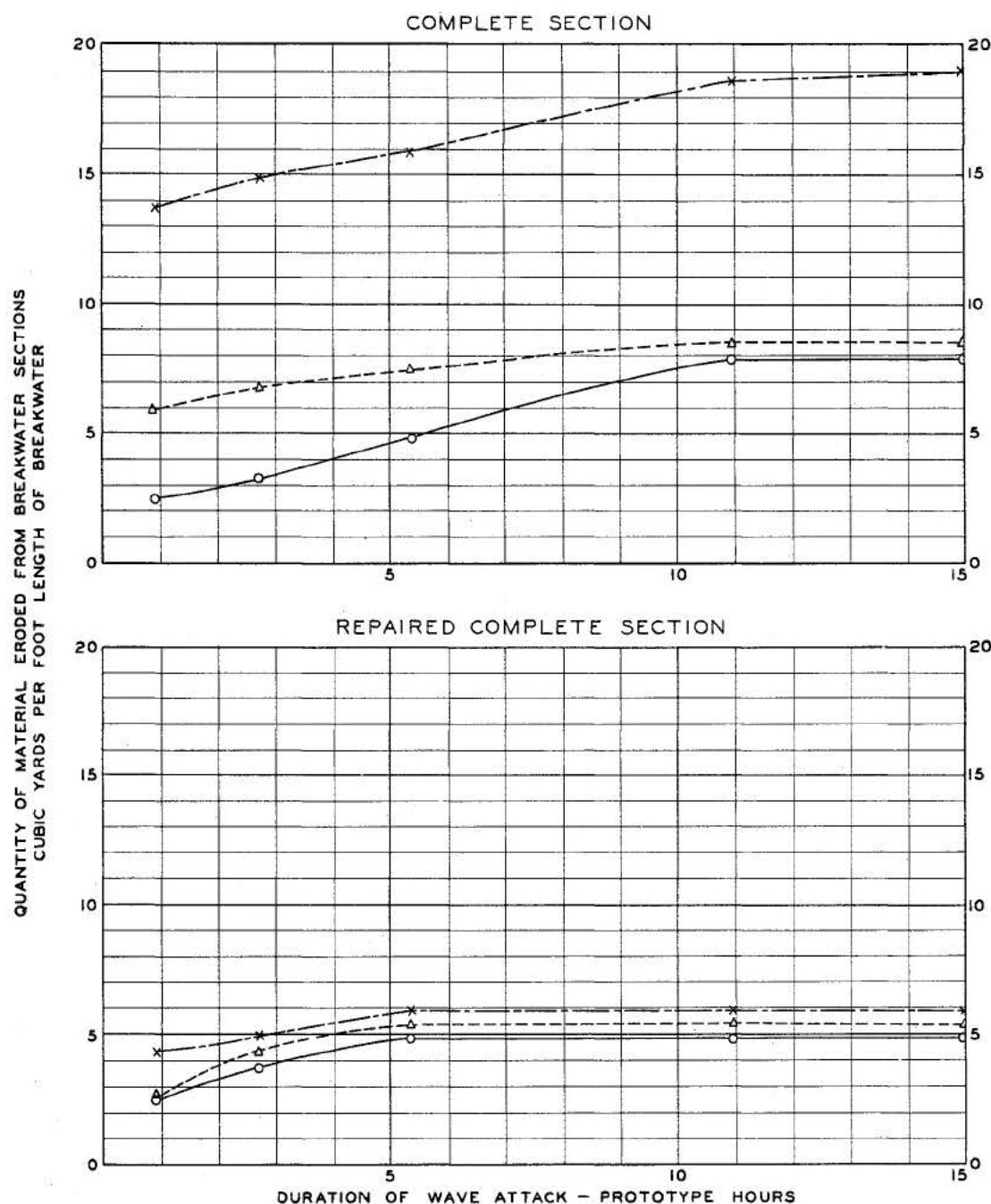
LEGEND

- 6FT X 160FT WAVE
- △---△ 10FT X 180FT WAVE
- ×---× 14FT X 240FT WAVE

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STORM DAMAGE TO  
BREAKWATER SECTIONS**

DESIGN I  
A- AND B- MATERIAL SECTION



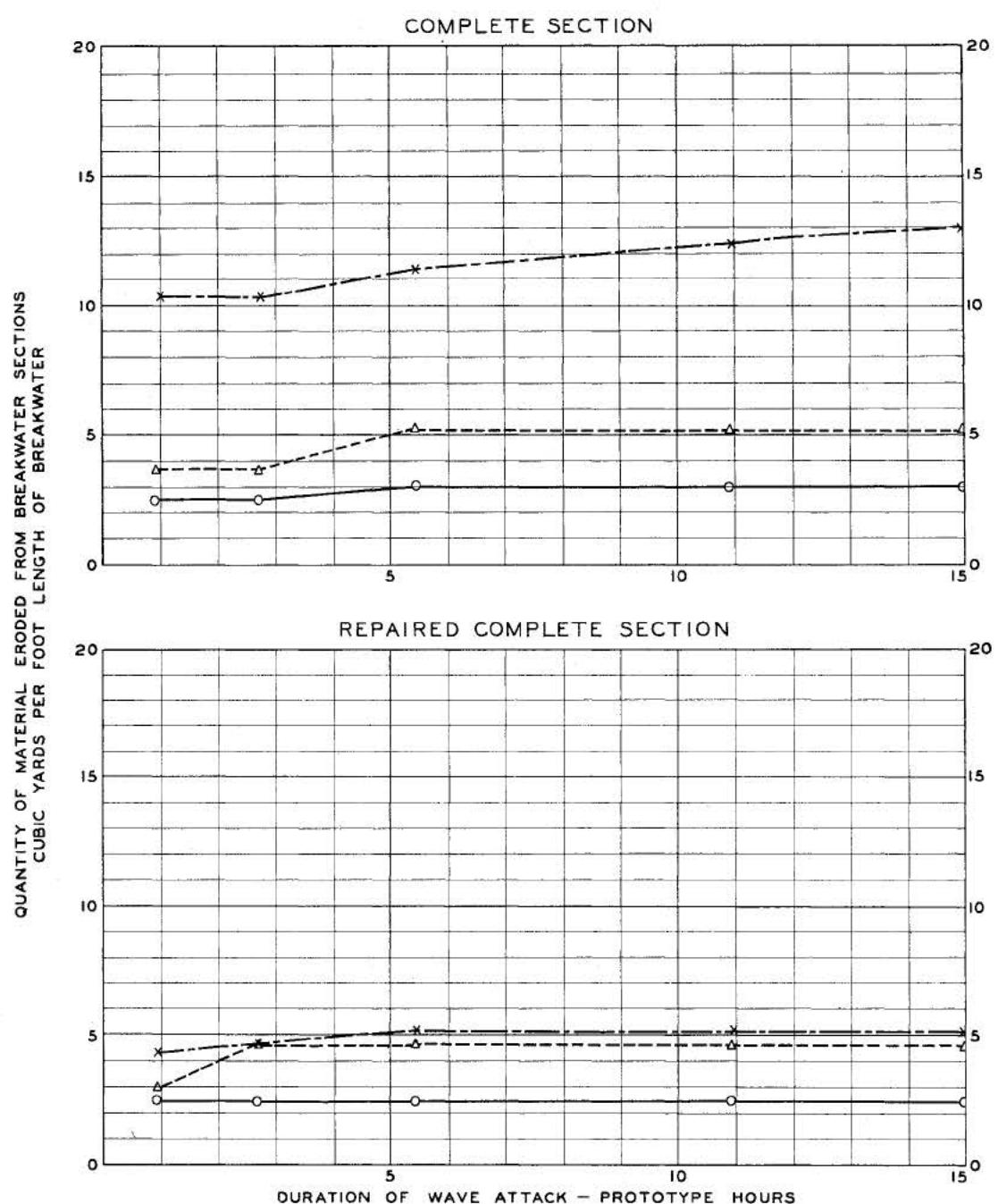
LEGEND

- 6FT X 160FT WAVE
- △---△ 10FT X 180FT WAVE
- ×---× 14FT X 240FT WAVE

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STORM DAMAGE TO  
BREAKWATER SECTIONS**

DESIGN I  
COMPLETE BREAKWATER SECTION



LEGEND

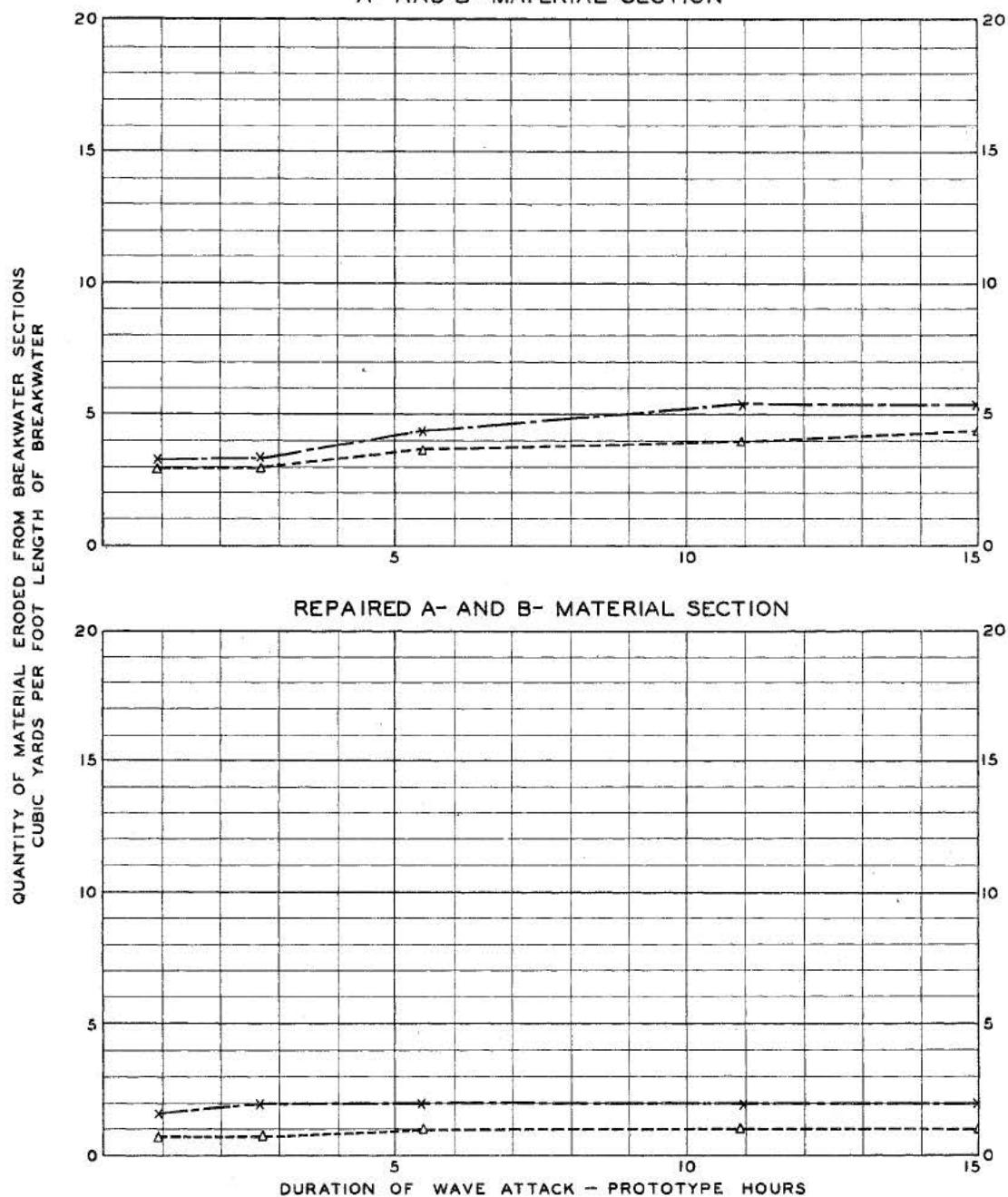
- 6FT X 160FT WAVE
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- ×---× 14FT X 240FT WAVE

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STORM DAMAGE TO  
BREAKWATER SECTIONS**

DESIGN IA  
COMPLETE BREAKWATER SECTION

A- AND B- MATERIAL SECTION



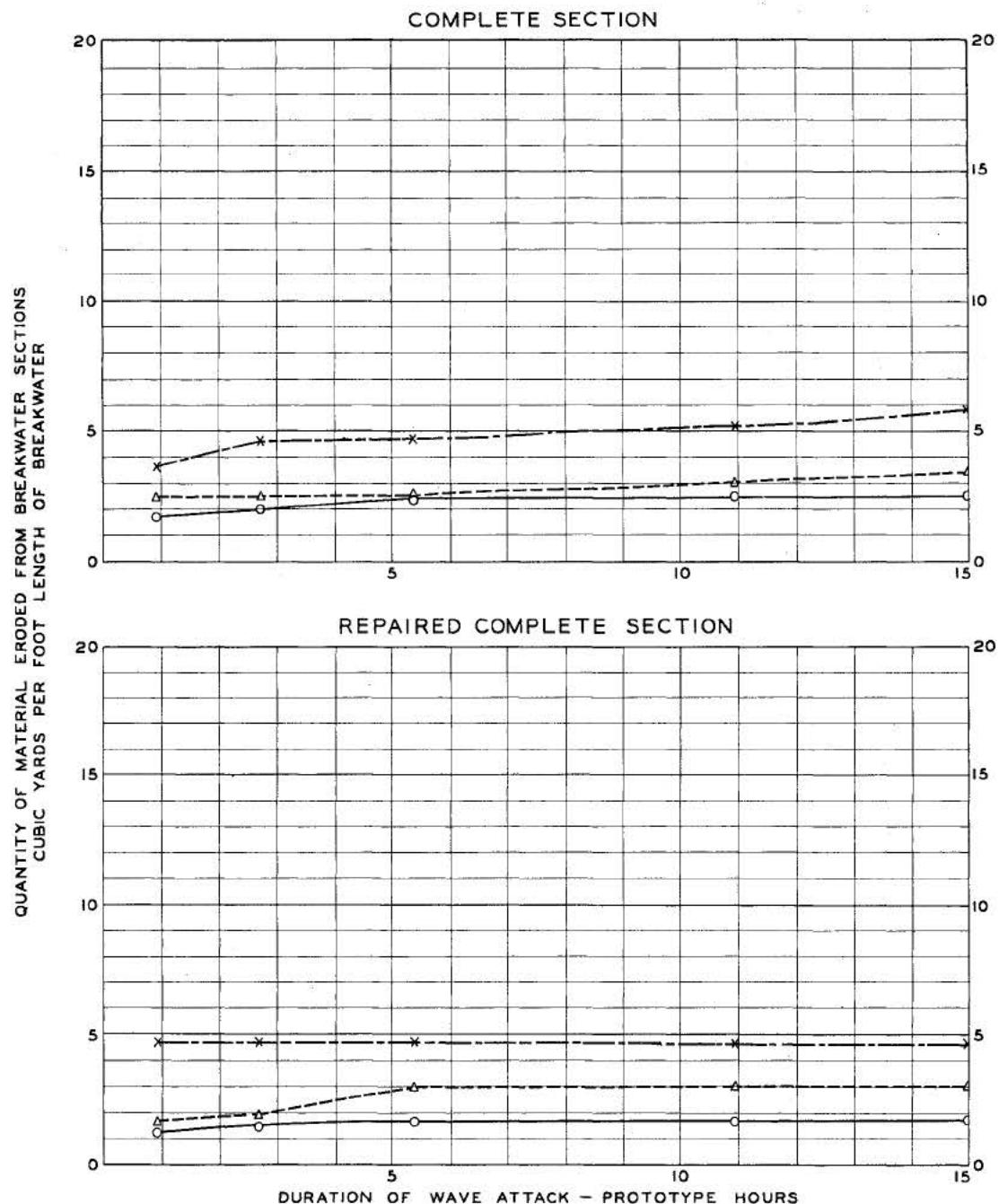
MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STORM DAMAGE TO  
BREAKWATER SECTIONS**

DESIGN 2  
A- AND B- MATERIAL SECTION

LEGEND

- 6FT X 160FT WAVE
- △---△ 10FT X 180FT WAVE
- ×---× 14FT X 240FT WAVE



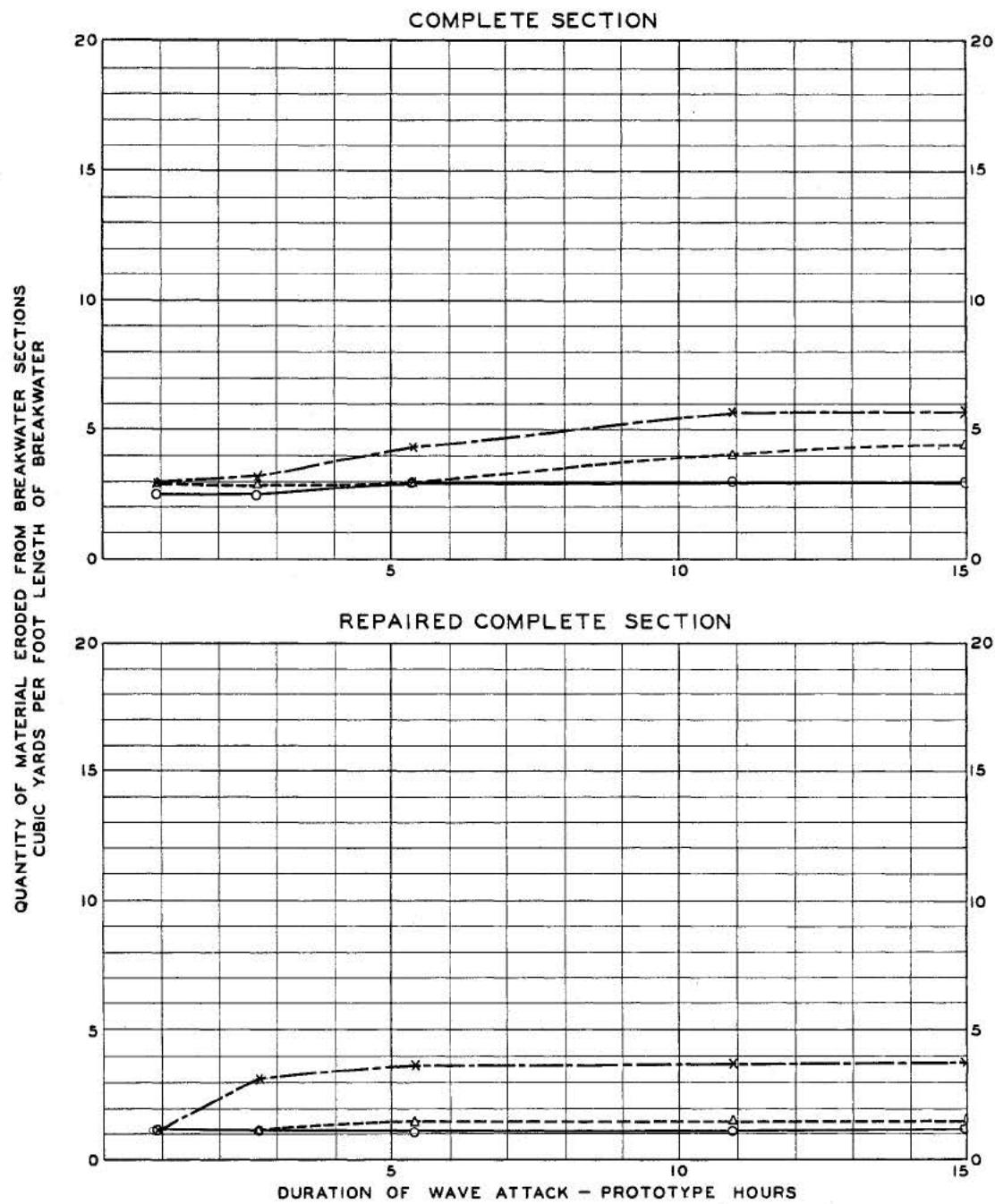
LEGEND

- —○ 6FT X 160FT WAVE
- △---△ 10FT X 180FT WAVE
- ×---× 14FT X 240FT WAVE

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STORM DAMAGE TO  
BREAKWATER SECTIONS**

DESIGN 2  
COMPLETE BREAKWATER SECTION



LEGEND

- 6FT X 160FT WAVE
- △---△ 10FT X 180FT WAVE
- ×---× 14FT X 240FT WAVE

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**STORM DAMAGE TO  
BREAKWATER SECTIONS**

DESIGN 2A  
COMPLETE BREAKWATER SECTION

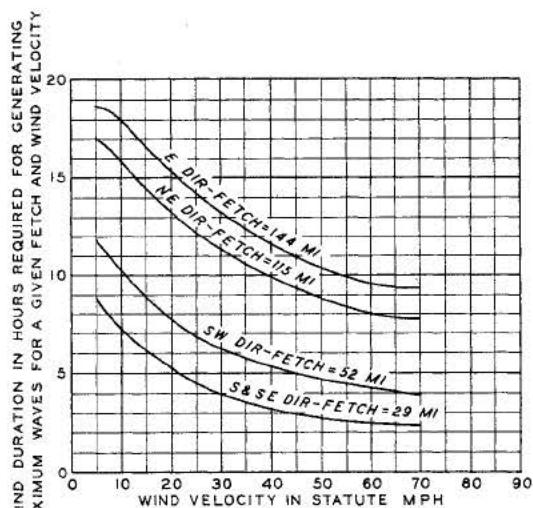


FIGURE 1: TIME IN HOURS REQUIRED FOR WIND OF GIVEN VELOCITY TO GENERATE MAXIMUM WAVES FOR A GIVEN FETCH.

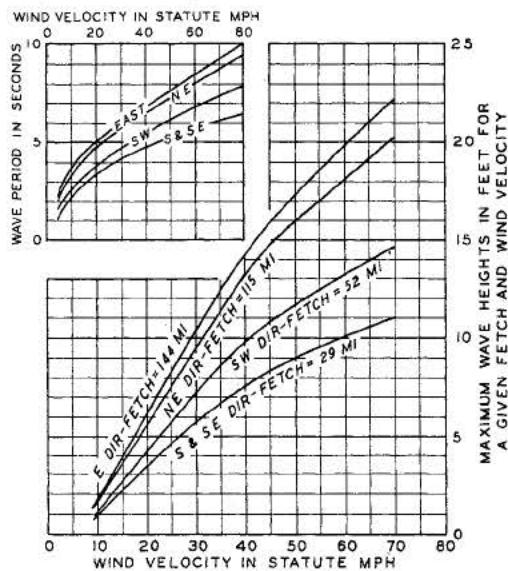


FIGURE 2: WAVE HEIGHT AND WAVE PERIOD AS FUNCTIONS OF WIND VELOCITY AND FETCH.

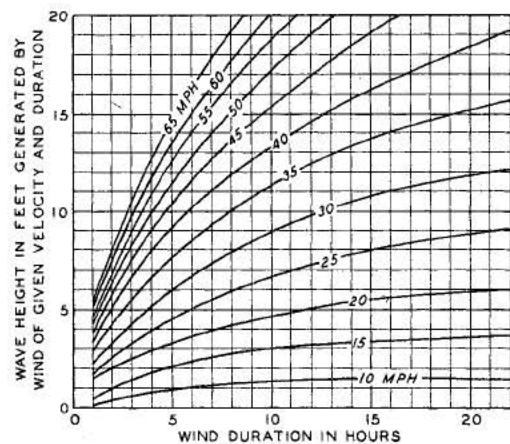


FIGURE 3: WAVE HEIGHT AS A FUNCTION OF WIND VELOCITY AND WIND DURATION.

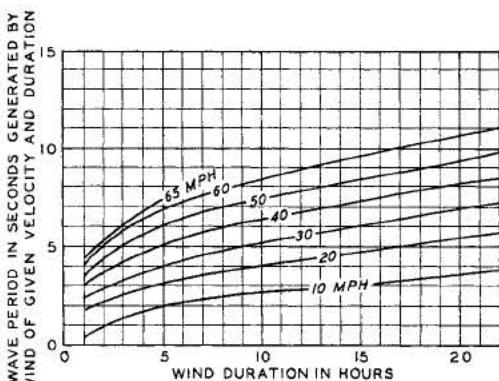


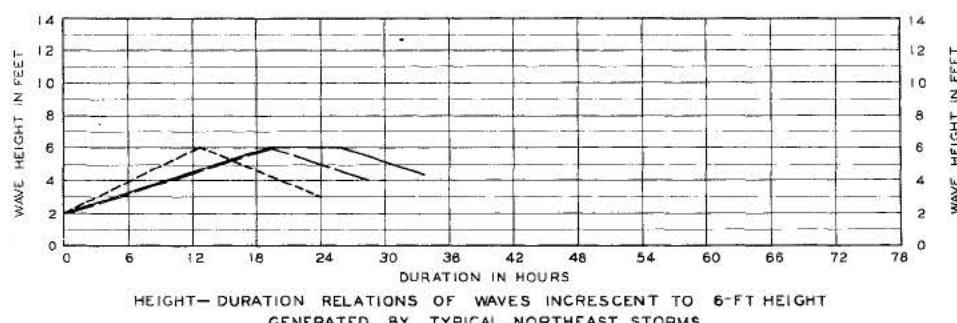
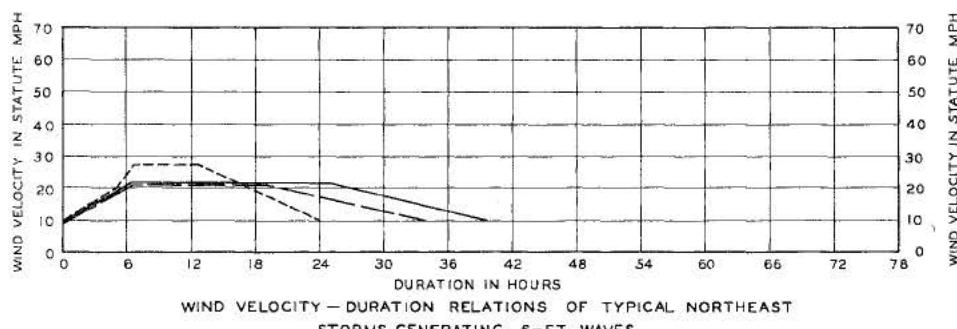
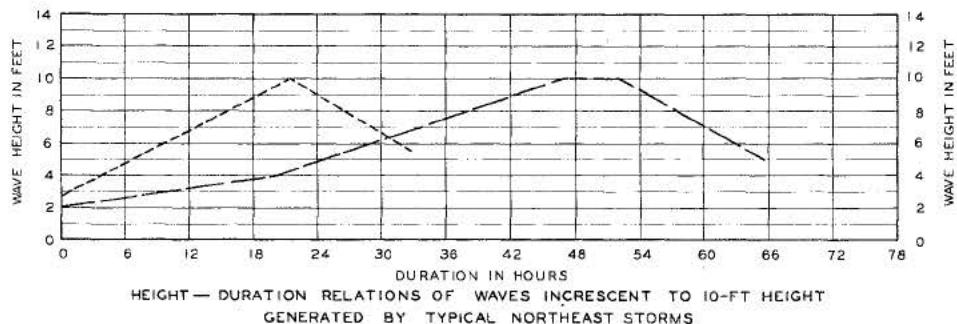
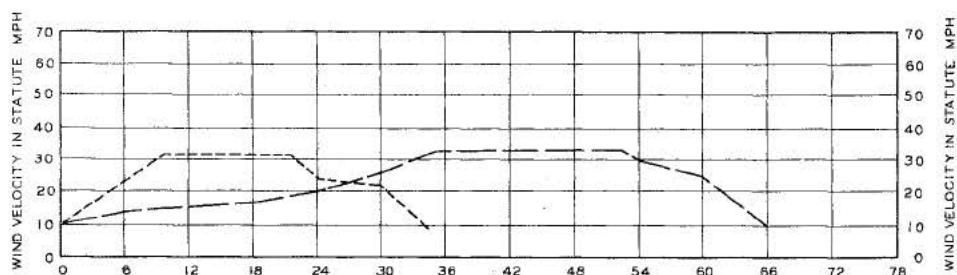
FIGURE 3A: WAVE PERIOD AS A FUNCTION OF WIND VELOCITY AND WIND DURATION.

NOTE: IN FIGURE 1 WHEN DURATION IS  $\geq$  REQUIRED FOR GENERATING MAXIMUM WAVES USE FIGURE 2 FOR DETERMINING WAVE HEIGHTS AND PERIODS; WHEN DURATION IS  $<$  REQUIRED FOR GENERATING MAXIMUM WAVES USE FIGURES 3 AND 3A.

CURVES SHOWING RELATIONS BETWEEN WIND VELOCITY, DURATION, FETCH AND WAVE CHARACTERISTICS WERE PREPARED BY WATERWAYS EXPERIMENT STATION FROM STEVENSON'S FORMULA AND DATA IN "WIND WAVES AND SWELL, PRINCIPLES IN FORECASTING" BY SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, LA JOLLA, CALIFORNIA.

MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

WIND - WAVE ANALYSIS  
RELATIONS BETWEEN WIND AND  
WAVES AT EAST BEAVER BAY



LEGEND

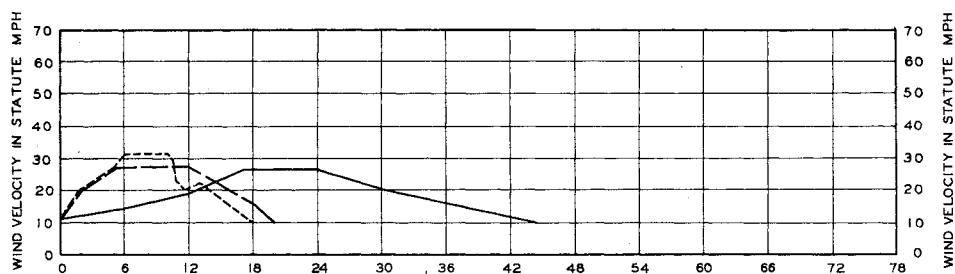
- STORM 1
- STORM 2
- STORM 3

NOTE: STORM NUMBERS REPRESENT THE PRINCIPAL TYPES OF STORMS FROM DIRECTIONS SHOWN WHICH GENERATE 6-FT AND 10-FT WAVES.

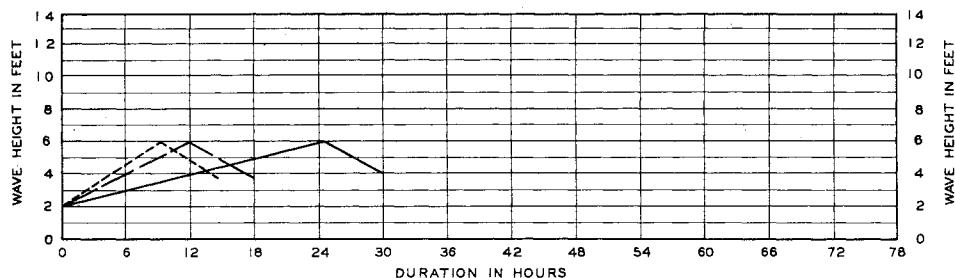
MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

**WIND—WAVE ANALYSIS**

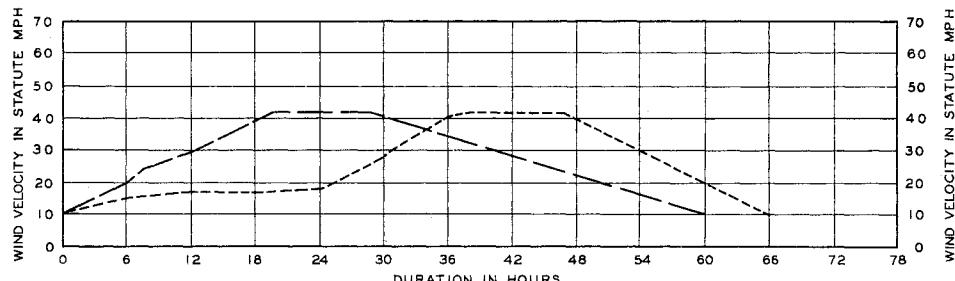
CHARACTERISTICS OF TYPICAL  
PROTOTYPE STORMS FROM DATA PREPARED  
BY CLARK AND FLOHR



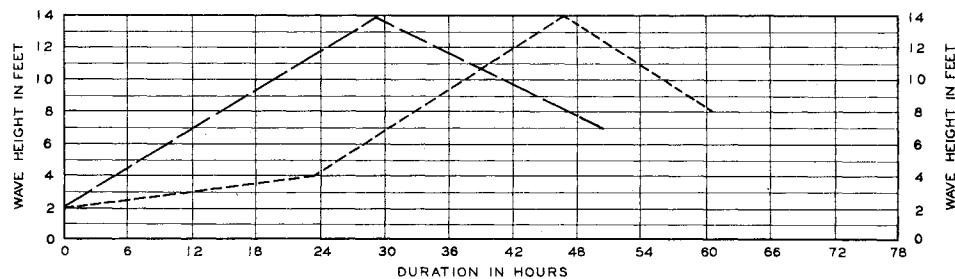
WIND VELOCITY - DURATION RELATIONS OF TYPICAL SOUTHWEST STORMS GENERATING 6-FT WAVES



HEIGHT - DURATION RELATIONS OF WAVES INCREMENTAL TO 6-FT HEIGHT GENERATED BY TYPICAL SOUTHWEST STORMS



WIND VELOCITY - DURATION RELATIONS OF TYPICAL NORTHEAST STORMS GENERATING 14-FT WAVES



HEIGHT - DURATION RELATIONS OF WAVES INCREMENTAL TO 14-FT HEIGHT GENERATED BY TYPICAL NORTHEAST STORMS

LEGEND

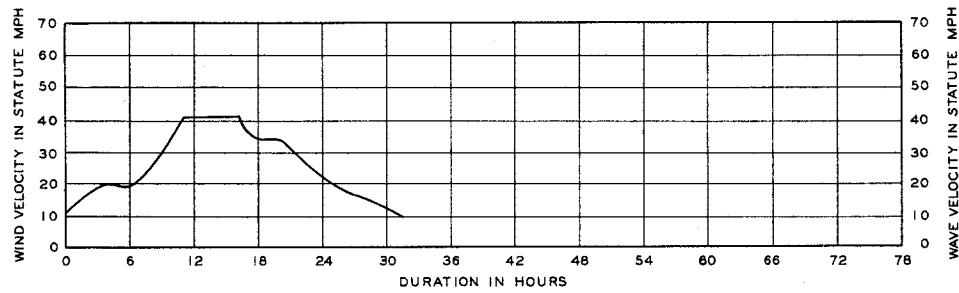
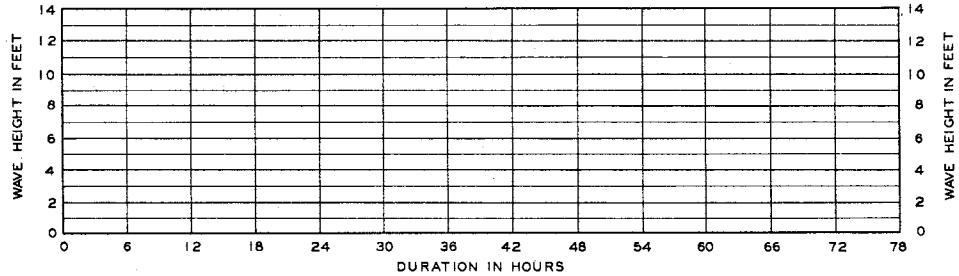
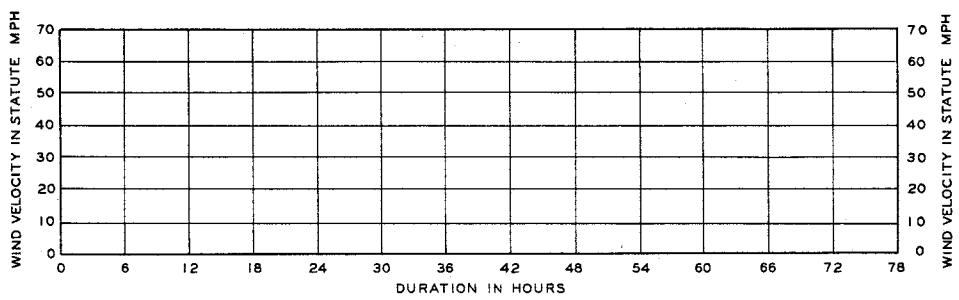
- STORM 1
- STORM 2
- STORM 3

NOTE: STORM NUMBERS REPRESENT THE PRINCIPAL TYPES OF STORMS FROM DIRECTIONS SHOWN WHICH GENERATE 6-FT AND 14-FT WAVES.

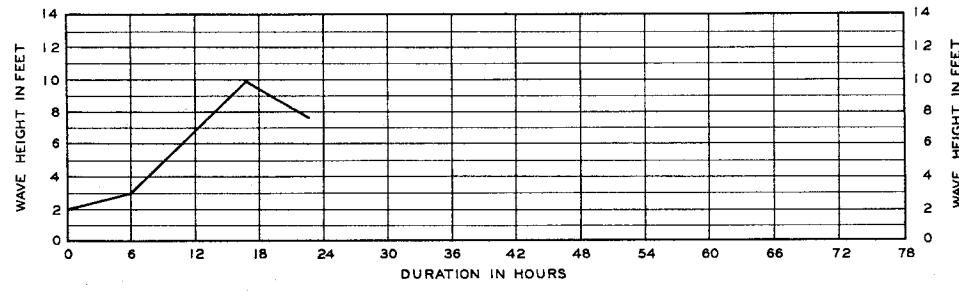
MODEL STUDY OF BREAKWATER STABILITY  
EAST BEAVER BAY HARBOR  
EAST BEAVER BAY, MINNESOTA

WIND - WAVE ANALYSIS

CHARACTERISTICS OF TYPICAL  
PROTOTYPE STORMS FROM DATA PREPARED  
BY CLARK AND FLOHR



WIND VELOCITY-DURATION RELATIONS OF TYPICAL SOUTHWEST  
STORM GENERATING 10-FT WAVES



HEIGHT-DURATION RELATIONS OF WAVES INCREMENTAL TO 10-FT HEIGHT  
GENERATED BY TYPICAL SOUTHWEST STORM

NOTE: THE TYPE STORM SHOWN ABOVE IS  
REPRESENTATIVE OF ALL SOUTHWEST  
STORMS WHICH RESULTED IN WAVES  
ABOVE 9 FT IN HEIGHT.

MODEL STUDY OF BREAKWATER STABILITY

EAST BEAVER BAY HARBOR

EAST BEAVER BAY, MINNESOTA

WIND-WAVE ANALYSIS

CHARACTERISTICS OF TYPICAL  
PROTOTYPE STORMS FROM DATA PREPARED  
BY CLARK AND FLOHR